DETERMINING PILOT MANNING FOR BOMBER LONGEVITY

THESIS

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Abstract

In support of US Air Force efforts to conserve resources without sacrificing capability, this research examines the question of whether the 509th Bomb Wing could continue to provide maximum combat capability with fewer assigned pilots. During peacetime, pilot proficiency training comprises the majority of annual flying hours for the small B-2 bomber fleet. Optimal pilot manning will decrease the accumulation of excess wear on the airframes; helping to extend the viable life of the B-2 fleet and preserve the deterrent and combat capabilities that it provides to the United States.

The operations and maintenance activity flows for B-2 aircraft and pilots in a notional sustained combat scenario are constructed in an Arena discrete-event simulation model. The model provides the capability to determine optimum manning levels for combat-qualified B-2 pilots across a range of fleet mission-capable rates. Determination of actual optimum manning levels is sensitive to duration and probability parameters; these are unavailable for use in this work. Notional parameter estimates are used to assess combat mission capability and pilot manning.

To my parents who taught me to always stay awake in class and to keep learning... To my wife and children who would have preferred that I had spent more time with them in the last eighteen months... To all of my Air Force friends and mentors who pushed me to jump in over my head, and to the AFIT grads who offered advice on how to breathe – especially Maj Kim Gonzalez, Maj Tim Porter, Maj Nate Nysether and Lt Col John VanHove... To my Savior, for the plan you have for me and for the strength that goes with it...

Thank You!

Acknowledgements

I would like express my appreciation to my thesis committee for their patience and assistance with my research; this has certainly been a learning experience. Special thanks go to Mr. Denny Benson for the MAJCOM analyst guidance and support which he offered and I gladly accepted. Dr. J.O. Miller – thank you sir for teaching me *this much* about combat models; it was invaluable to my research.

I owe a debt of gratitude to my research sponsor and the men and women of the 509th and 131st Bomb Wings. You provided me with a research topic which proved both interesting and challenging and allowed me another opportunity to work with the best plane in our inventory.

Jason S. Hamilton

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I. Introduction

> Meeting real-world requirements. Doing right by our people. Reducing excess. Being more efficient. Squeezing costs. Setting priorities and sticking to them. Making tough choices. These are all things that we should do as a department and as a military regardless of the time and circumstance. But they are more important than ever at a time of extreme fiscal duress, when budget pressures and scrutiny fall on all areas of government, including defense. When every dollar spent on excess overhead or unneeded programs ... is a dollar not available to support our troops and prepare for threats on the horizon. [8]
>
> – Robert M. Gates, US Secretary of Defense

1.1 Background

The US military has been asked to "do more with less." As a result, development of a number of planned new weapon systems has been canceled and the operational lifespan of some systems must be extended rather than even consider replacing them. With the US and world economies struggling to emerge from a recession, practicing responsible stewardship of the nation's resources is as vital now as it has ever been.

In several recent speeches, the US Secretary of Defense has expressed his support of US Air Force missions in spite of recent difficult budgetary constraints [9]. "Far from being a skeptic of air power," Gates offered to cadets at the US Air Force Academy, "I believe that air supremacy - in all its components will be indispensable to maintaining American military strength, deterrence, and global reach for decades to come." "America's nuclear deterrent - including the missile and bomber legs maintained by the Air Force - will remain a critical guarantor of our security, even as the nation works toward the long term goal of a world without nuclear weapons."

The US Air Force must make informed decisions in the unending quest to provide security to America's citizens and allies and deterrence to those who would be our enemies.

1.2 Case Study

The United States Air Force's 509th Bomb Wing (BW) and the Missouri Air National Guard's 131st Bomb Wing[1] operate, maintain, and train for combat using 19 (out of 20) B-2 Spirit long-range stealth bombers. The B-2 was originally designed and tasked to be a nuclear-only first-strike bomber but the end of the Cold War required a change in tasking for the then relatively new aircraft. It also caused the procurement of the planned 135-aircraft fleet to be halted at only 21. Although the 509th BW is under the authority of the newly-formed Air Force Global Strike Command (AFGSC), which is responsible for the nation's nuclear deterrent forces, the B-2 can still be assigned conventional strike missions. The B-2 has been employed as a conventional first-strike bomber in Operation Allied Force (Bosnia, 1999), Operation Enduring Freedom (Afghanistan, 2001), Operation Iraqi Freedom (Iraq, 2003), and Operation Odyssey Dawn (Libya, 2011).

The B-2 mission capable (MC) rate has been in decline for several years. Mission capable rate is a measure used across the Air Force to report whether systems are capable of performing their peacetime or wartime missions [4:17]. The primary cause for the slipping MC rate is the difficulty of obtaining parts to replace those which wear out sooner than anticipated. The B-2 is such a highly specialized aircraft, and such a small number were built, that manufacturing and stocking replacement parts, other

[1]The 509th Bomb Wing and the 131st Bomb Wing jointly operate and maintain the B-2 fleet at Whiteman AFB. Throughout this research, references to the 509th BW also apply to the 131st BW.

than those which were designed to have a limited life, presents logistical difficulties. Many of the original manufacturers have gone out of business, taking specialized production capability with them. For many of the parts, mass manufacturing and long-term storage is not a feasible option because the small fleet cannot take advantage of the economy of scale which would drive prices down. The alternative, manufacture of single parts as they are needed, causes aircraft to sit idle and their missions to be either canceled or shifted to the other B-2s. This load shifting in turn causes the other aircraft in the fleet to age faster than anticipated.

Although the B-2 does not need to fly combat missions very often, the small fleet is under a high degree of stress. The number of aircraft available for peacetime flying at any time hovers around half the fleet or fewer. Approximately every seven years, each aircraft goes offline for a full year of programmed depot maintenance (PDM) – a near-complete disassembly and inspection followed by replacing the life-limited parts as well as any parts which the inspections reveal need early replacement. With this schedule, approximately three B-2s are in PDM at any given time [16]. Additionally, it is not uncommon for one or two B-2s to be parked for several months at a time for the installation of upgraded components (communications equipment, radars, *etc.*). As mentioned, there are often a few B-2s awaiting replacement parts. As an operational bomber and part of the United States' nuclear deterrent, several aircraft are always kept available for real-world contingency use.

Those few remaining B-2s have to accommodate the entirety of the 509th Bomb Wing's daily flying activities; the majority of which involve pilot training or maintaining currency. As B-2 pilots retire, new pilots are trained to replace them. Each new pilot requires an average of 10 five-hour training sorties. As of November 2010, there were around 100 B-2 pilots actively assigned to the flying and training units at WAFB, each required to meet minimum flying currency standards as established by the Federal Aviation Administration and the Air Force's Ready Aircrew Program (RAP). Depending on the specific tasking level associated with a pilot's assignment within the 509th BW, RAP requirements are one or two four-hour sorties per month. Considering that each flying sortie has a crew of two pilots, the RAP requirements equate to over 1,000 sorties (4000 flying hours) per year.

Other B-2 sortie requirements are for testing, verification, and yet more training. Operational test sorties are required to certify upgrades to components, weapons, and software. Flight safety verification sorties are required after major locally-performed maintenance. Weapons School pilots accomplishing advanced tactics training have a flying syllabus to complete which includes local training sorties and deploying with B-2s and maintenance personnel to Nellis AFB, Nevada for Red Flag and other combat exercises.

The sponsor of this research would like to explore the possibility that there may currently be too many pilots assigned to the 509th Bomb Wing and that reducing pilot manning may improve fleet health and longevity. This premise is explored in this research.

1.3 Research Objective and Scope

The objective of this research is to develop a model representing B-2 combat operations which may be used to analyze and determine the combat-qualified pilot manning levels for 509th Bomb Wing under a variety of scenarios. It is proposed that an optimal manning level will allow the 509th BW to offer the maximum level of combat force to the President of the United States and relieve some of the stress on the airframes, helping to sustain the B-2 fleet as a viable weapon system into the foreseeable future.

The objective of this research is to develop a technique which may be used to analyze and determine the combat-qualified pilot manning levels for 509th Bomb Wing. It is proposed that an optimal manning level will allow the 509th BW to offer the maximum level of combat force to the President of the United States and relieve some of the stress on the airframes, helping to sustain the B-2 fleet as a viable weapon system into the foreseeable future.

The research presented here is based on unclassified information representative of the system under study. The actual times, probabilities, and capacities for maintenance and operations activities are unavailable for public release, but the structure of the model is valid and represents a simplification of the 509th Bomb Wing's historical B-2 combat operations. After this initial notional study, Air Force Global Strike Command's Analysis & Assessment Division (AFGSC/A9) will be given a working copy of the model so that they may include actual data and generate the type of results that are presented in this research.

The remainder of this document is organized as follows:

- Chapter Two contains a survey and discussion of several categories of published research which deal with similar topics.
- Chapter Three details the development of the research simulation model and explains how each component relates to the problem.
- Chapter Four consists of descriptions and analysis of the results of this research under several different scenarios.
- Chapter Five presents a summary and overall conclusions.

II. Review of Related Literature

Published research is available which addresses various aspects of properly selecting manning levels for organizations. Many of the methods of addressing general manning determination are dependent on other techniques used to generate the schedules and shifts for the application in question. The research areas examined in the development of this work are primarily related to transportation crew scheduling and the assignment of aircraft to flying routes. Work related to scheduled carriers, not only airlines, is also applicable to several aspects of the bomber pilot manning problem. Section 2.3 details the unique aspects which separate this research from available studies that have been previously published.

2.1 Published Airline-Related Research

Transportation industries, and the airlines in particular, must accomplish optimization at multiple points in the process of planning for efficient scheduled operations. The names used for the optimization steps required vary, but the specific functions and their objectives are fairly consistent across the published research and practices in place. Several authors list the sequence of optimization problems as *schedule planning, fleet assignment, aircraft routing, crew pairing, and crew rostering*; this sequence is used to explore the research available [21, 15].

Due to the size of each problem type and differences in structure and objective, typical practice is to consider the optimization problems independently and in series. Sandhu and Klabjan [21:439] identify that "only selected subsets of two of these problems are modeled and solved as a single integrated problem, *e.g.*, fleeting and aircraft routing, and aircraft routing and crew pairing." They give further examples of the interdependency of the problem stages; noting that some problems are solved over subsets of others, decomposed by crew-equipment compatibilities and other tactical issues.

2.1.1 Schedule Planning.

The initial step in the airline schedule optimization considered by most authors is the *schedule planning* phase. Here, the daily flight schedule with origin, destination, and departure and arrival times, is constructed for the entire network of airports served [21:439]. The majority of the published schedule planning research uses the assumption that all flights in a schedule are repeated daily. Breaking the problem daily into an identical (or nearly identical) repeating pattern of flight segments simplifies the solution process and is a valid simplification because many airline flight schedules operate in this manner, with slight deviations for weekend and holiday travel [10, 21].

2.1.2 Fleet Assignment.

Fleet assignment, or *fleeting*, involves the assignment of an equipment type (or fleet) to each of the flight legs planned in the previous step. An aircraft fleet is defined by the passenger capacity, operating cost, speed, crew requirement, maintenance requirements, *etc.*, for the equipment types used by the airline (*e.g.* Boeing 767-223ER, CRJ 700, MD-80). Fleet assignment models seek optimal solutions in which each flight leg is serviced by the most cost-efficient aircraft type in order to maximize profit – usually the smallest type which meets the typical demand for number of passengers on the leg, minimizing the average number of empty seats [21, 12, 22]. However, according to Abara [1], "The best aircraft for each flight leg is not always the one with the highest benefit because, among other reasons, aircraft must be routed for maintenance, and the number of available aircraft is limited."

Abara explains four "intrinsic constraints" on any solution to the fleet assignment problem [1:22-23]:

- An aircraft completing one flight with an arrival may be used for a subsequent departing flight as long as there is sufficient connection time between the two for aircraft servicing and loading. *"Flight coverage"* guarantees that each flight leg departing an airport is assigned to no more than one aircraft.
- A flight can include multiple legs and each flight is assigned to a single fleet type. *"Continuity of equipment"* ensures the integrity of the fleet assignment logic by requiring that every leg in a flight is served by the same aircraft type.
- *"Schedule balance"* allows more of either arrivals or departures at an airport by forcing some flights to terminate during the day and creating a new flight on a different aircraft type. This practice is commonly seen by passengers changing planes during a flight connection.
- *"Aircraft count"* helps to minimize costs by assigning flights to the minimum possible number of total aircraft.

After fleet assignment has been accomplished, each of the subsequent problem steps is considered separately for each fleet type. The model proposed by Sandhu and Klabjan [21:439] "simultaneously considers fleeting, the plane-count requirement in aircraft routing, and crew pairing." The purpose for such ambitious integration is to avoid the suboptimal solutions which are inevitably accepted when the problems are considered separately.

2.1.3 Aircraft Routing [21:442].

Aircraft routing is the sequencing of the flights for each aircraft and includes normal passenger flights and scheduled stops for routine maintenance at particular locations. Because of differences in the types of flight legs assigned and maintenance requirements, the aircraft routing problem is solved separately for each aircraft fleet type.

2.1.4 Crew Pairing.

Crew pairing is the first of the airline-related problems which considers personnel. Anonymous crews are generated to meet the requirements from the fleet assignment and aircraft routing stages. The purpose is to assign aircrews to each of the flights on the schedule such that personnel costs are minimized. Each aircraft fleet type may require a unique makeup of the crew members (pilot, first officer, flight attendants) and each must have the proper qualifications. Crew pairing includes not only generating the aircrews, but also sequencing several flights, potentially over multiple days, which start and end at a city where the crew is based. Normal personnel costs include the crew salaries and hotel and taxi fees that are necessary when crews must spend the night away from their crew base. Costs can increase above the normal levels because crews are guaranteed a minimum number of paid hours per day while traveling, even if they do not actually fly for that amount of time [21:442-443]. Crew salaries and travel pay make up the second most expensive portion of airlines' budgets, second only to fuel [10, 15]. Excess costs are minimized through careful crew pairing and schedule optimization. According to Sandhu and Klabjan,

> The crew-pairing problem is difficult to solve due to the following two reasons. The number of pairings and thus variables, is in the order of billions even for a medium-size fleet family of 200 flights. Also, the calculation of the cost of a pairing is very complex within dynamic generation of pairings, and a large number of complicated rules need to be taken into account while generating pairings. [21:443]

Pairings also must satisfy several types of rules in order to be valid. Federal aviation safety regulations limit maximum consecutive flying time and mandate the length of rest periods between duty days or flights. Union and airline-specific rules may further impose minimum time off, minimum pay for flight legs or duty days, and maximum number of flight hours in a set time period for pilots [21, 15, 10, 20].

2.1.5 Crew Rostering.

While some authors consider crew pairing and crew rostering to be part of the same problem, the majority of published research separates the two.

The crew pairing problem generates the required classes of aircrews from the available crew member types, ensuring that each flight has a feasible aircrew makeup. Regarding *crew rostering*, each specific instance of an aircrew is generated by assigning particular individuals to the aircrew for each flight. This is the stage in which an employee's actual work schedule is produced. In addition to the flight legs, additional activities may be added to each individual schedule at this point; examples include off-duty time, training, *etc.* Crew rostering also considers personal preferences and quality of life aspects for the airline's employees – most airlines use a bidline system in which individuals express their preferences for particular flights and schedules. [15]

Figure 1 and the following text are excerpted from the thorough work by Kohl and Karisch on the crew pairing and rostering problems, and are applicable to the current research.

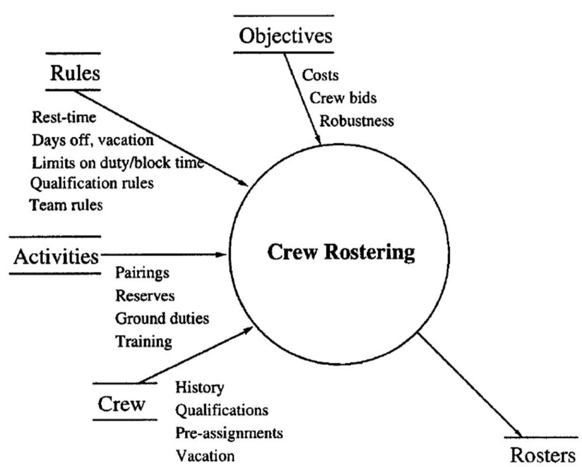

Figure 1. Representation of Inputs to the Airline Crew Rostering Problem [15:228]

> The input for a crew rostering problem consists in general of crew information, activities to be rostered, rules and regulations, and objectives

> for the creation of the rosters. However, when creating bidlines, *i.e.*, anonymous rosters, individual crew aspects are not considered.
>
> When producing personalized rosters, each crewmember's personal records, qualifications, pre-assigned activities, and vacation days are given. The records usually contain accumulated attributes such as hours flown during the current calendar year. Other values of interest are due dates for training or possible exceptions from certain rules and regulations. Personal qualifications contain for instance information about the equipment the crewmember can operate or a list of destinations the crewmember cannot fly to. For cabin crew, language proficiency is an important qualification for international flights. Pre-assigned activities could be training, office duties or medical checks.
>
> The set of activities which are assigned consists of pairings, reserves (*e.g.*, airport and home standby duties), ground duties (*e.g.*, medical checks), and training activities (*e.g.*, simulator training and courses). [15:227-228]

The methodology for the research into bomber pilot manning is most closely related to the crew rostering problem because of the requirements that crew schedules must satisfy flight safety rules, consider pilot qualifications, and include training and other duties.

2.2 Published Solution Methods

Operations research (OR) methods have been applied to airline-related problems since before 1960 [17:3]. Broad categories of OR tools employed include mathematical programming, networks, heuristics, simulation, as well as combined approaches. The following sections provide brief examples of some of these techniques as they have been applied to airline-related problems.

2.2.1 Mathematical Programming.

Linear programming, integer programming, and mixed-integer programming are the most common approaches applied to find solutions to airline and even more general scheduling problems. The flexibility of the objective and constraint structures of the varieties of mathematical programming are quite well suited to airline problems which are intended to minimize cost or maximize profit. Examples of constraints which must be fulfilled are: takeoffs must equal landings; each flight requires an aircraft and a particular number of crew members – each with particular qualifications; and so on.

In 1989 J. Abara published a relevant paper on the application of integer programming (IP) to the fleet assignment problem. The paper, which has been cited nearly 200 times in published literature alone, provides an overview of the fleet assignment problem for American Airlines and an easy-to-read definition of the entire IP model in use at the time. Abara suggests that one objective to be maximized may be "utilization of the most efficient aircraft," and that possible constraints are limits on "the number of aircraft that remain overnight at a particular station" (due to space restrictions) and daily "limits on arrivals or departures" at an airport [1].

According to Kohl and Karisch, most methods for solving the crew rostering problem are based on the "*generate-and-optimize principle*." First "a large number of legal rosters is generated" in the generation subproblem, meeting safety and contractual rules. Then a logically-selected subset of those rosters is examined and "a set partitioning type problem is solved to select exactly one roster for each crewmember such that the demands of the activities are met, the solution satisfies constraints between several crewmembers, and the objective is optimized" [15:224]. "The assignment constraints make sure that each crewmember gets assigned exactly one roster," and "the activity constraints ensure that each activity is assigned exactly once in the solution" [15:226].

2.2.2 Networks.

Network models can be readily applied to the airline problems because of the point-to-point nature of the flights and connections in space and time. Gu, Johnson, Nemhauser, and Wang [12:59] approach the fleet assignment problem as a "min-cost multicommodity flow problem on a time-space directed graph."

Sherali, Bish, and Zhu [22:3-4] detail two different representations of the fleet assignment models using a network structure. For a connection network structure, a node-arc graph is created which represents all feasible flight connections at a single airport in one day. "Nodes represent points in time when flights arrive or depart" and the network includes imaginary source and sink nodes to symbolize aircraft beginning or ending the day at the airport. The three types of possible connections are illustrated by three types of arcs. *"Originating (connection) arcs"* link the aircraft available at the beginning of the day with the possible departure nodes. "*Flight connection arcs* link the arrival nodes to the departure nodes." And *"terminating (connection) arcs"* link the arrival nodes to the imaginary sink node when the aircraft overnight at the airport. Feasible flight connections (those allowing adequate turn time) are the focus of this type of network representation, and the solution assigns aircraft types to the set of arcs which maximizes expected revenue, ensuring that all connections are included.

Time-space network structures focus on the flight legs and the model assigns connections, dependent on time and space feasibilities. This structure reduces the number of decision variables "because the number of flight legs is far lesser than the number of possible connections." It is noted that since this network structure was first applied to fleet assignment in 1993, it has become the preferred approach. The interested reader is referred to the referenced tutorial for an example and further details. [22:6]

2.2.3 Simulation.

Simulation is a modeling tool which is often used to compare alternative scenarios or to identify bottlenecks within a system. Hafizogullari, Chinnusamy, and Tunasar [13] used discrete event simulation to study the flow of passengers transferring between airline flights in a proposed new terminal at a major airport. Their research examined "minimum connect time" and "passenger walking distance" as performance measures to compare alternative terminal designs. The rationale for their choice of simulation is both interesting and applicable to the study of bomber pilot manning because of the potential for bottlenecks and interdependencies.

> Accurately modeling the operation of a real-world process over time, such as the flow of passengers through an airport, can result in problems of immense magnitude and complexity. Although many operations research techniques such as linear/integer programming, stochastic programming, and queuing theory provide valuable insights, they often fail to represent large-scale problems that arise in airport terminal design due to poor scalability or excessive computational burden. We use simulation modeling to represent operations in a terminal building because of its ability to capture complex relationships and scalability. The processes at an airport are interdependent. Separate modeling and optimization of individual components may result in sub-optimal solutions. Simulation addresses this problem by quantifying the interdependencies and finding bottlenecks. Solving one bottleneck may cause another bottleneck to develop somewhere else in the system and the modeler needs to consider the total system performance. [13:1193]

Gosavi, Ozkaya, and Kahraman [11] employed simulation-based optimization to solve an airline seat-allocation problem, optimizing the number of seats assigned to each fare class in order to maximize profit while considering realistic policies and some random occurrences. They note that "simulation can easily accommodate realistic assumptions (such as cancellations and overbooking), which often render theoretical models intractable" [11:22].

Rosenberger *et al.* [20] used a stochastic discrete-event simulation model to study the effects of flight disruptions (*e.g.*, cancellations and delays) on airline schedules and performance. Their model includes all of the aspects of daily flight operations, at an appropriate level of aggregation, and may be used to test how an airline's recovery policies should affect the solutions to the fleet assignment, aircraft routing, and crew scheduling problems.

2.3 Unique Aspects of this Research

Much of the staffing level optimization research available in the published literature deals with either minimizing cost or maximizing profit and is not directly applicable to the objectives of this work. This research is focused on developing a model which may be used to determine efficient manning levels for a military bomber aircraft fleet and is unique from other works available due of the extreme length of the employees' tasks and particularly because the scheduling of each shift is dependent on resource availability rather than on a fixed schedule. The aim of the model developed through this research is to maximize the number of combat missions that can be flown while minimizing unnecessary strain on the aircraft and the parts and maintenance system through identifying potential overages in manpower. Successfully executed combat missions can serve as the measure of performance for the 509th Bomb Wing in this research and the "cost" to be minimized is the physical wear on the B-2 fleet. The employees of interest are the B-2 pilots, and only a portion of their schedule is of interest. The only shifts examined are those directly related to flying the B-2 missions. Aside from pre- and post-mission rest and duties, this research is not concerned with any of the pilots' activities (*e.g.*, ground duties or training activities) when they are not actually flying a mission.

While airline, retail, and most other shift scheduling research primarily deals with shifts shorter than 24 hours, each B-2 mission in this research occupies the pilots for over 100 consecutive hours. The daily schedule repetition assumption is not applicable to the long-duration bomber mission problem and unnecessary because the creation of detailed crew schedules is not considered. The military environment and the "at war" scenario preclude serious consideration of some of the scheduling factors presented in section 2.1.5.

One example of manning research with similar long-duration scheduling requirements is a study to determine the annual firefighter staffing level which minimizes pay and overtime, while ensuring coverage of both short-term and long-term absences [7]. Another paper which proved helpful in the development of this research was Gershkoff's work on flight crew schedule optimization [10:34-36]. His general strategy of exploring and capturing all of the rules and constraints applicable to the manning problem is reflected in the model development methodology in Chapter 3. The methodology, scenario, and model design for this research are detailed in Chapter 3.

III. Methodology

3.1 Research Methodology

This research examines the impact of pilot manning levels and B-2 mission capable rates on overall combat capability. A discrete-event simulation model of B-2 combat operations is produced which provides the number of combat missions executed with varying numbers of available pilots and B-2 aircraft. The model simulates 90 days of continuous combat missions and analysis demonstrates that there exists a pilot manning level at which combat capability would not suffer, regardless of the B-2's mission capable rate.

3.1.1 Discrete-event Simulation.

When using a simulation model, all items of interest are represented by *entities* which travel along a fixed path, stopping at the *modules* (sometimes called *blocks*) which represent activities. A discrete-event simulation uses the simplifying constraint that an entity's state may only be changed at discrete points in time.

Discrete-event simulation is chosen as the method with which to approach the current bomber pilot manning research. The stochastic nature of the interrelated operations and maintenance activities is easily translated into a delay-driven schedule-flow simulation. The potential to identify bottlenecks, the capability to compare alternative scenarios (*i.e.*, pilot manning levels), and the ease of updating model parameters when additional data becomes available, all make simulation an ideal tool for analyzing the manning question.

As an example, consider a morning commute to work. The entity represents the commuter and its first state is *at home*. At some point in time the commuter leaves home and is now *commuting*. The end of the commute is signaled by arrival *at* *work*. Initially, these three states may not seem adequate to characterize someone's morning routine. However, defining important milestones in the schedule as boundaries between the three states and allowing the proper amount of time in each state, successfully defines the morning in discrete events. For this example, say *at home* requires an average of one hour to get ready, eat, *etc.*, then leaving the driveway begins *commuting*, which usually takes 25 minutes, and finally, stepping into building the commuter is *at work*.

One purpose of a discrete-event simulation is to gain insight about how changes affect a system. The next step in the *morning commute* model could be to examine the possibility of changing the route taken to work. The benefit of a simulation is that it can make the commute thousands of times and report back statistics on how long the average morning routine is likely to take. To provide this type of insight the model requires certain data.

3.1.2 The Triangular Distribution.

Each time an entity arrives at a block representing an activity or a decision, the simulation model needs to randomly select a duration or probability to apply to the entity. A triangular distribution is helpful when the amount of data available about an activity's duration is limited, but good estimates of the range of times that it may take, as well as its most likely duration are available. Generally the shortest possible, longest possible, and most likely durations are represented by the symbols $a, b,$ and c, respectively.

The probability distribution function (PDF) for the triangular distribution and a continuous random variable X (representing an activity's duration in this model) is defined by Equation (1). The value of the PDF represents the probability of X falling between any two *fixed* values between the lower limit, a, and the upper limit, b [14].

A general example plot for the triangular distribution PDF is illustrated in Figure 2. The total area under the plotted line equals one, which is to be expected because the activity duration must fall between a and b and thus the probability that $a \leq x \leq b$ must equal 1.

$$f(x) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & \text{for } a \leq x \leq c \\ \frac{2(b-x)}{(b-a)(b-c)} & \text{for } c \leq x \leq b \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

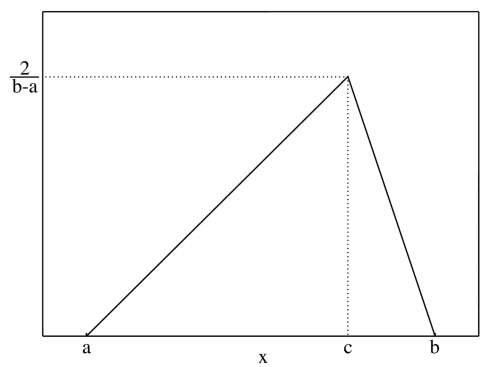

Figure 2. Triangular Distribution PDF Example Plot [23]

In the morning routine example, let the random variable x represent the commute time for any day and assume that the commute can never be shorter than 15 minutes ($a = 15$), never longer than 30 minutes ($b = 30$), and usually takes 25 minutes ($c = 25$). The continuous property of the triangular distribution mirrors reality in that commute times may be fractions of minutes (*i.e.*, 22.4 minutes). Also, by definition, the duration of the commute is always between fifteen and thirty minutes so $P(15 \leq x \leq 30) = 1$.

The cumulative distribution function (CDF) for the triangular distribution is defined by Equation (2). As it is used in this model, the value of the CDF represents the probability that the randomly selected value of the duration X will be less than or equal to a *fixed* value, x, within the activity's possible range of durations. Figure 3 is a plot of the CDF of a general triangular distribution and, along with Table 1, will be helpful in explaining the CDF. Table 1 lists some potential values for x, where x is the commute length in the morning routine example. The CDF identifies that there is only a 6% probability of making the commute in 18 minutes or less, but the probability of making the commute in 27 minutes or less is 88%.

$$F(x) = \begin{cases} \frac{(x-a)^2}{(b-a)(c-a)} & \text{for } a \le x \le c \\ 1 - \frac{(b-x)^2}{(b-a)(b-c)} & \text{for } c \le x \le b \end{cases} \tag{2}$$

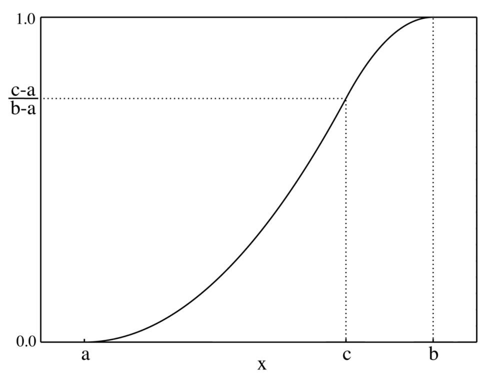

Figure 3. Triangular Distribution CDF Example Plot [23]

Table 1. Triangular Distribution CDF Example Data

Value of x	15	16	17	18	19	20	21	22
Cumulative Probability	0.000	0.007	0.027	0.060	0.107	0.167	0.240	0.327
Value of x	23	24	25	26	27	28	29	30
Cumulative Probability	0.427	0.540	0.667	0.787	0.880	0.947	0.987	1.000

A simulation model uses a random number generator (RNG) to select activity durations, but generally, RNGs generate random numbers between 0 and 1. Since value of the CDF is also between 0 and 1, the CDF may be inverted by solving it for the value of X. Equation (3) is the triangular inverse CDF. The input variables for the inverse CDF are the triangular distribution parameters a, b, and c, and a random number U between 0 and 1. The model uses the triangular inverse CDF to map each random number to a feasible outcome (*e.g.*, an activity duration).

$$X = \begin{cases} a + \sqrt{(b-a)(c-a)U} & \text{for } a \leq x \leq c \\ b - \sqrt{(b-a)(b-c)(1-U)} & \text{for } c \leq x \leq b \end{cases} \tag{3}$$

For the morning routine example, the primary variable of interest is *commute time*. When the entity arrives at the *commuting* block, the simulation draws a random number, say 0.88, and applies the inverse CDF. Since the inverse CDF with $U = 0.88$ gives $X = 27$ (also note that 0.88 was the probability that the CDF associated with a 27 minute or faster commute time) the simulation uses 27 minutes for the commute time on this particular day. Figure 4 illustrates the mapping from 0.88 to 27 using the inverse CDF for this example. Since commute time is random for each day, it will be assigned a different random value on the next day.

3.1.3 Common Random Numbers.

When it is necessary to compare simulation results across different model conditions, such as two routes to work, it is preferable to have confidence that the observed differences were caused by intentional changes to the model, not merely by the randomness of the random numbers. This is accomplished through the use of *common random numbers* (CRNs), a strategy which allows the generated random numbers to be synchronized across simulation runs. When using CRNs, each variable is assigned the same sequence of random values every time the simulation is run. So for the morning routine example, let the model simulate three months with traveling via

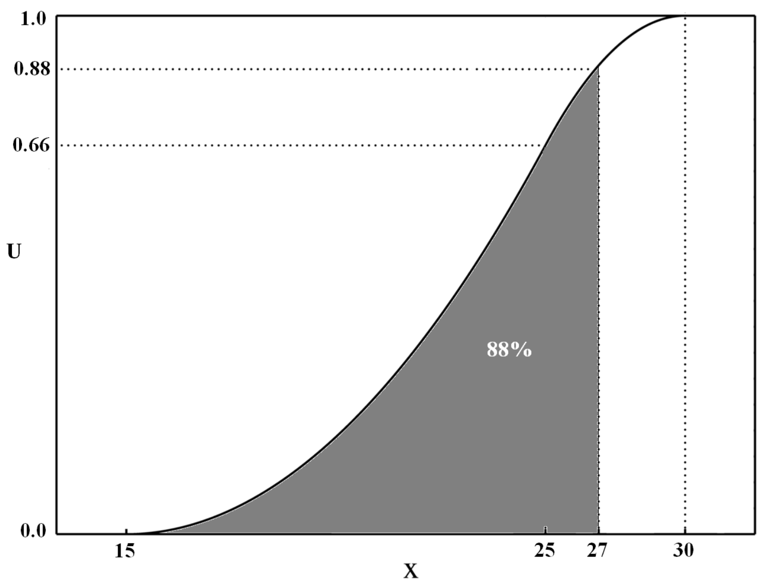

Figure 4. Triangular Distribution Inverse CDF Example Plot [23]

route (1) and three months traveling via route (2), the same random number will be used to generate the commute time on any specific day in both cases. This way there is no potential of the simulation generating all commute times on the short end of the expected range for route (1) and all commute times on the long end for route (2).

3.1.4 Analysis Strategy.

Each run of the B-2 combat flow simulation consists of 90 days of continuous combat missions. The primary variables of interest in this research are the B-2 mission capable (MC) rate, which can be translated into how many aircraft are available for operational tasking, and the number of assigned combat-qualified pilots. A variable of secondary interest is the number of pilots sent ahead to the mission stopover location to ferry B-2s back to Whiteman Air Force Base (WAFB). The practice of transporting pilots to another location as passengers is called "deadheading" and is further explained in section 3.2.2.

For each level of B-2 mission capable rate examined (section 3.3.2), the number of combat-qualified pilots and the number deadheading to the stopover location are independently varied and the number of completed combat missions recorded. The model is used to explore wide ranges for both values in order to observe trends in the output, both above and below the values yielding the apparent optimal pilot manning level.

It is proposed that for each B-2 MC rate studied with this model there exists a pilot manning level which, if exceeded, does not contribute to the 509th Bomb Wing's total combat capability (as defined by the number of combat missions completed in 90 days). This point of diminishing returns is labeled the *indicated optimal* B-2 pilot manning level. The indicated optimal pilot manning levels for the various MC rates provide insight into the effect of less than ideal aircraft mission capability on both combat capability and aircraft overuse due to possible overmanning.

3.2 Scenario Development

The B-2 has flown in combat in Operation Allied Force (OAF) (Bosnia, 1999), Operation Enduring Freedom (OEF) (Afghanistan, 2001), Operation Iraqi Freedom (OIF) (Iraq, 2003), and Operation Odyssey Dawn (Libya, 2011). Although it was initially intended to be a nuclear-only bomber, the B-2's long range and immense payload capability has earned it a leading role in modern conventional warfare. In order to explore pilot manning and combat capability, this research employs a discrete-event simulation model representing a simplified version of daily pilot and aircraft operations at the 509th Bomb Wing during a notional combat scenario.

The scenario is designed to simulate a high degree of stress on the operations and maintenance processes of the 509th Bomb Wing. In the scenario, the 509th BW is tasked to provide as many conventional combat missions as possible in 90 days. A

90-day bombing period is chosen as a reasonable expected maximum length that the B-2's capabilities would be required. B-2s flew combat missions in support of OAF for eight weeks [2]. The simulated bombing campaign is chosen to be conventional, rather than nuclear, in order to allow a longer scenario.

The purpose of the scenario is to simulate the structure of the actual B-2 operations and maintenance processes using entities for the pilots and the B-2s. Simulating the operational scenario provides the number of combat missions completed under the given conditions.

3.2.1 Simplified Scenario.

This section describes the mission flow for both the pilots and the B-2s in a simplified combat scenario and has the purpose of familiarizing the reader with the B-2 operations included in this research. Missions flown under this scenario launch from WAFB, fly into combat, then return to WAFB. This type of nonstop tound-trip combat mission was employed in OAF, OEF, and Operation Odyssey Dawn [2]. Figure 5 depicts the flow of all activities which impact the schedules of all the B-2s and pilots for this simplified scenario.

The dotted-bordered boxes in the upper third of Figure 5 represent all of the activities which occur for every B-2 before and after a combat mission. The solid-bordered boxes in the middle are the mission activities which require both a B-2 and an aircrew. Activities involving only the pilots are shown in the dashed-bordered boxes in the lower third of the figure.

When the order to go into combat is received by the 509th BW, all available B-2s and pilots can be tasked immediately. The available B-2s are loaded with the munitions required for the combat mission. Available pilots are batched into aircrews consisting of two pilots and assigned a combat mission. The aircrews mission-plan for

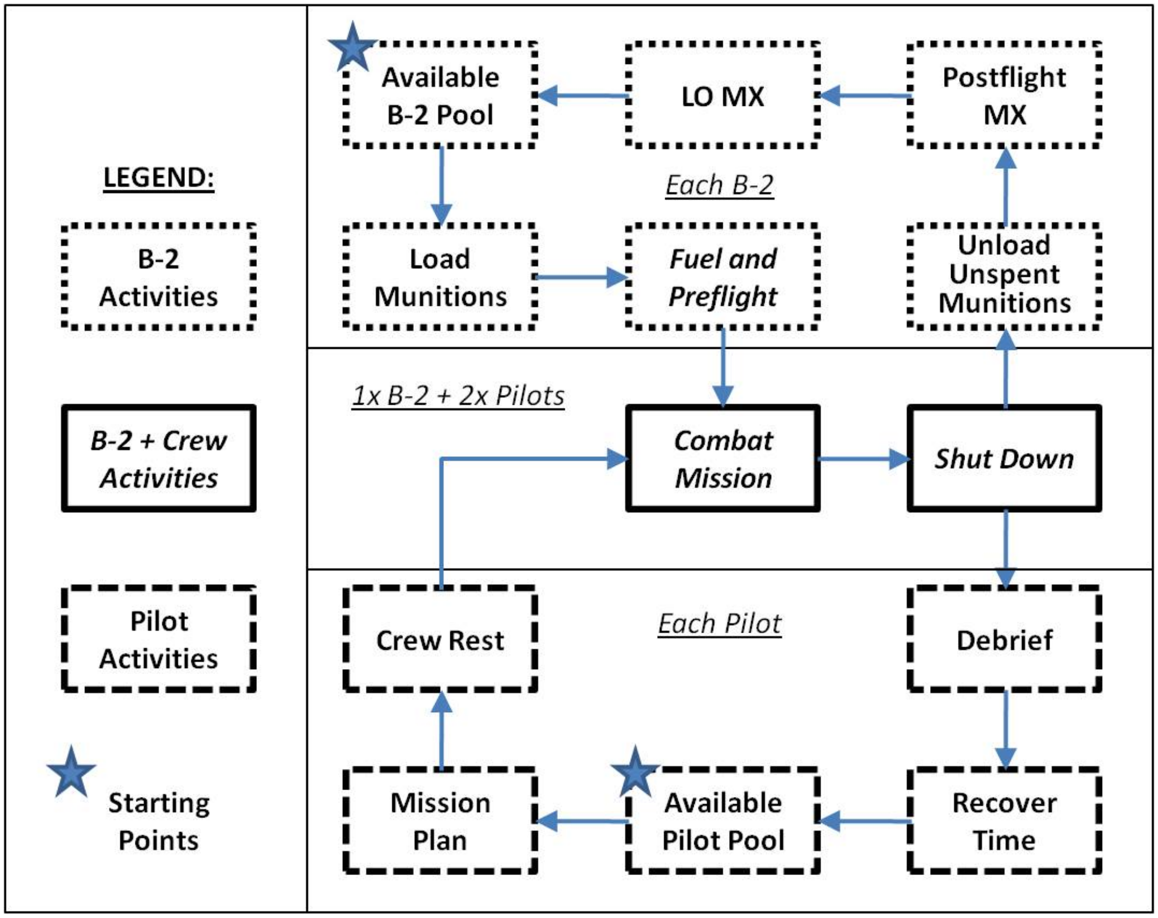

Figure 5. Simplified Scenario Mission Flow

approximately one working day, familiarizing themselves with the mission's routing, targets, and other important details. The aircrew members are then given 48 hours to rest in preparation for the long-duration mission. Shortly before the planned takeoff time, the B-2 is fueled and readied for flight. In this scenario, B-2 preflight procedures are performed by a spare aircrew in order to allow the mission aircrew to begin their flight as rested as possible.

The aircrew completes their combat mission, lands back at WAFB, then shuts down the B-2, a process which includes running multiple checklists and completing aircraft performance-related paperwork. At this time, the pilots accomplish their post-mission debriefing and then are allowed time to rest and return their bodies to a normal work/sleep schedule. This pilot recovery time is set at 30 hours in this research. Once the pilots have completed their post-mission recovery, they resume their normal day-to-day jobs within the bomb wing until they are assigned another combat mission.

After the B-2 is shut down, any munitions which were not expended in combat are unloaded and returned to the weapon storage and staging area. Maintenance personnel then accomplish routine post-flight maintenance and inspections and conduct unscheduled maintenance to repair any additional problems. After maintenance, the low observable coatings on the exterior of the B-2 must be touched up, especially if damage from hitting birds, flying through hail, *etc.* during the mission was noted. After the B-2 is returned to the proper operating condition, it is available to be assigned to another combat mission. A modification of these interwoven schedule cycles is executed continuously for 90 days for every B-2 and every pilot in this research model.

3.2.2 Research Scenario.

The simplified scenario described in section 3.2.1 represents, for instance, the political worst-case situation where the United States may not be allowed to land the B-2 in any foreign country and is forced into making round-trip combat sorties. The simplified scenario could also be used if the target area is close enough to the US that the duration of a round-trip combat mission would not be overly long. This section describes the scenario which is implemented in this research and was employed in OIF. Although it is more complex, this scenario is preferable because it decreases the risk of pilot fatigue and therefore is safer for both the pilots and the aircraft.

In order to reduce pilot fatigue during combat missions in this scenario, the B-2s land at a stopover location and undergo minimal post-flight maintenance. A fresh aircrew then returns the B-2 to Whiteman AFB. The stopover location could be any properly-equipped location within several hours of flight from the combat area. In past operations, both Guam and Diego Garcia have been used as stopover locations [16]. Depending on the location of the combat area and the stopover location in relation to WAFB, performing the stopover could cut sixteen hours or more off of the combat mission. Any reduction in flight time from the post-combat phase of the mission greatly decreases the risks to the pilots who will have been flying for over twenty four hours and whose adrenaline will likely be depleted.

Figure 6 depicts the activity flow for B-2s and pilots for the scenario used in this research. In the diagram for this scenario, all activities for the B-2 only are in the center, pilot-only activities are on the left for WAFB and on the right for the stopover location, and mission activities (requiring a B-2 and an aircrew) are at the top and bottom.

The basic activity flow is identical to that of the simplified scenario; with modifications only to accommodate flight operations from two locations. As detailed in section 3.3.9, it is assumed that limited maintenance support is available at the stopover location.

At the beginning of the 90-day combat simulation, a portion of the B-2 pilots travel via commercial airline or military transport to the stopover location. This practice of having pilots travel without performing any crew duties is called “deadheading” and is expensive to the Air Force both in terms of travel costs and lost productivity in those pilots’ jobs at WAFB [10, 20]. Deadheading pilots to the stopover point is necessary in this scenario in order to keep the B-2s in the air as much as possible. Without deadheading pilots, once a B-2 lands at the stopover, it sits idle until the aircrew that flew it in combat recovers from the combat flight, mission-plans, and rests for the flight back to WAFB, an 80-hour sequence on average in this research.

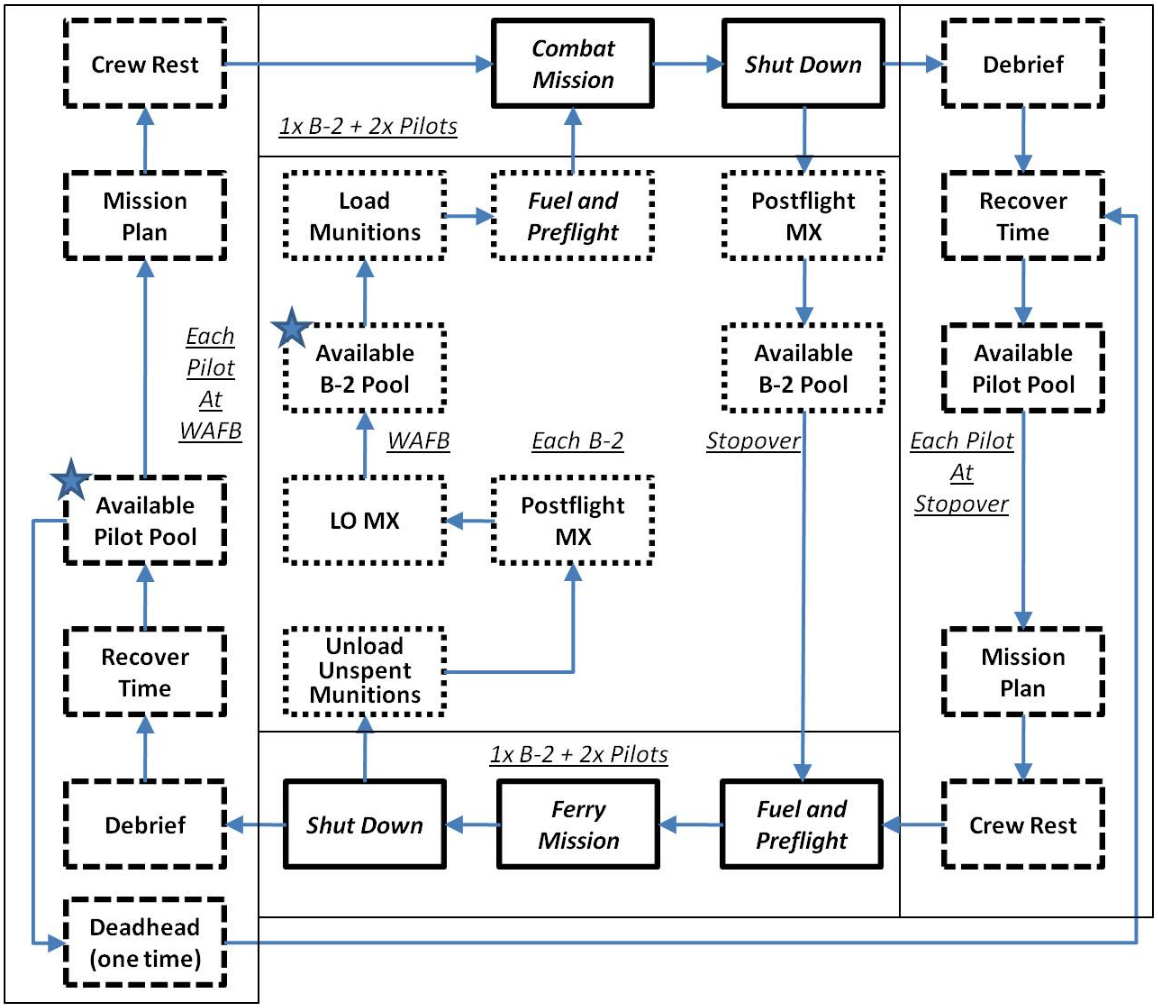

Figure 6. Research Scenario Mission Flow

The deadheaded pilots at the stopover location form the starting population for a secondary available pool of rested pilots who are available to ferry each B-2 back to WAFB as soon as post-flight maintenance is completed.

As the second round of combat missions are completed, the pilots who were initially deadheadeded are replaced at the stopover location by pilots just coming from combat. If mission timing is correct, the pilots from the first round of combat missions are recovered, have mission planned the ferry mission back to WAFB, and are completing their crew rest as the B-2s become available. This rest-combat-rest-ferry pattern is repeated by all of the pilots over the 90-day scenario and is initially jump-started by the deadheaded pilots. Given enough pilots are initially deadheaded, this model keeps each B-2 on the ground at the stopover location for an average of only 15 hours, 65 hours fewer than without deadheading.

The primary risks in deadheading pilots to the stopover location are that either too few or too many are sent. As discussed previously, too few deadheaded pilots cause B-2s to sit idle at the stopover. Sending too large a fraction of the B-2 pilots to wait at the stopover degrades the ability of the 509th BW to maintain efficient combat operations because many of the pilots are stuck at the stopover location and there are fewer pilots at WAFB to conduct normal operations. A secondary objective of this research is to determine the appropriate number of pilots to deadhead for each of the B-2 mission capable rates and pilot manning levels explored.

3.3 Model Design

The simulation model built for this research matches the structure of the research combat scenario described in section 3.2.2. The discussion that follows provides details on both the additional logic required to represent the scenario in a discrete-event simulation as well as the triangular distribution parameters used for the activity durations.

The independent input variables are:

- The number of B-2s available for combat (which is a function of the mission capable rate as explained in section 3.3.2).
- The total number of combat-qualified B-2 pilots assigned to operational units at Whiteman AFB.
- The number of B-2 pilots deadheaded to the stopover location.

The output value of interest from the simulation is the total number of *completed combat missions* for each combination of the input variables.

Figures 11 and 12, presenting the model structure, and Table 9, listing the activity duration distributions for each block in the model, are found in Appendix A.

3.3.1 Fleet Size.

The original B-2 fleet consisted of 21 aircraft; 20 assigned to Whiteman AFB for training and operations, and one assigned to Air Force Flight Test Center at Edwards AFB, California. One of the WAFB aircraft crashed on takeoff from Anderson AFB on Guam in February 2008 and was declared a total loss [18]. In February 2010, another B-2 suffered an engine fire and will be returned to service after a complete overhaul [3]. This research model assumes that all 20 remaining aircraft will be committed to combat operations.

3.3.2 Aircraft Availability.

As defined in AFI 10-603, an aircraft is reported to be *fully mission capable* (FMC) if it can perform all of its assigned missions and *partially mission capable* (PMC) if it can perform at least one, but not all, of its assigned missions [4:35]. Mission capability codes are reported for each individual aircraft and aggregated across the entire B-2 fleet. A particular aircraft is *not mission capable* (NMC) if it cannot perform any assigned missions – for example, when it is disassembled for maintenance. The mission capable rate for a time period is calculated using Equation 4. Possessed hours for each B-2 is the amount of time during the period in question that the 509th Bomb Wing actually has operational control of the aircraft. Examples of nonpossession would be when a B-2 is in programmed depot maintenance (PDM) or is undergoing a major modification. In these cases the prime contractor, Northrop Grumman, is in possession of the aircraft and that time is excluded from the denominator of the MC rate equation.

$$\text{MC Rate} = \frac{\text{FMC hours} + \text{PMC hours}}{\text{Possessed Hours}} \times 100 \tag{4}$$

Air Force Times published the mission capable rates for all USAF aircraft systems for the fiscal year ending September 2010, these rates are are included in Appendix B. The 2010 mission capable rate for the B-2 fleet was 54.86% [19]. When the Air Force sets a goal for a system MC rate, they must "consider system operating time ... in that the more a system operates in a given period of time, the more downtime for corrective and preventative maintenance is required [4]." Considering this statement, and the definition of MC rate, a mission capable rate of 100 percent is not possible because every aircraft requires downtime, at the least for preventative maintenance, and eventually for unscheduled maintenance. The premise of this research is that it is possible to identify a pilot manning level which allows the 509th BW to deliver maximum combat capability and reduces the number of peacetime training sorties to a level which requires less corrective maintenance downtime and thus increases the B-2's MC rate.

One of the primary variables explored in this simulation model is the B-2 MC rate. With 20 total B-2s in the fleet, this research assumes that three are in PDM, leaving 17 in the possession of the 509th Bomb Wing. With 17 aircraft committed to the combat effort, this research explores the impact that various MC rates would have on the number of combat missions executed. It is assumed that all of the logistics, maintenance, and operations infrastructure and manning are at the levels required to generate each particular fleet MC rate. Working under this assumption, the model is not required to include maintainer manning, parts supply, *etc.*

B-2 combat capability is investigated using four levels of the MC rate: 53%, 65%, 76%, and 88%. Selection of the MC rates to explore is based on what are deemed to be reasonable values for NMC time per week. Equation (4) is rearranged into

Equation (5), converting a given MC rate into average mission capable hours per aircraft per week. The average number of hours per week that each aircraft is not mission capable is then given by Equation 6.

$$\text{MC Hours per week} = 24 \times 7 \times \frac{\text{MC Rate}}{100} \tag{5}$$

$$\text{NMC Hours per week} = (24 \times 7) - \text{MC Hours per week} \tag{6}$$

By Equation (5), the FY 2010 MC rate translates to an average of 76 hours of NMC time per week for each B-2. For comparison, average weekly MC and MNC time per aircraft using the published 2010 MC rates are given in Appendix B for all US Air Force aircraft systems. The four MC rates explored in this research span values of 20 NMC hours per week to 79 NMC hours per week.

With 17 B-2s committed to combat and the fleet performing at a particular MC rate, that percentage of the fleet is in a mission capable state at any time, on average. Table 2 gives the average number of B-2s available for executing combat missions under the chosen MC rates in this model, along with the corresponding average values for MC hours and NMC hours per week. In each case it is planned to use all 17 B-2s in combat but, on average, the number over the calculated available limit are nonflyable. In reality, these nonflyable aircraft are the causal factor behind the mission capable rate.

Table 2. B-2s Available for Combat Varies According to MC Rate

MC Rate	B-2s Available	MC hours per week	NMC hours per week
53%	9	89	79
65%	11	109	59
76%	13	128	40
88%	15	148	20

3.3.3 B-2 and Pilot Simulation.

The simulation scenario begins with the order for the 509th Bomb Wing to prepare for war and terminates after 90 days. In a realistic scenario, when the execution order arrives, some of the B-2s would be flying standard peacetime missions, others might be undergoing post-flight maintenance, and several would be hangared in perfect maintenance condition awaiting war orders. Allowing the simulation software to begin at time zero with all of the mission capable B-2s ready and available would not capture this time spacing effect between aircraft. This is simulated by allowing the B-2 entities to enter the simulation according to an exponential distribution, with a mean time between arrivals of four hours. The first B-2 is immediately available and the others become available as time progresses.

Pilot availability at the start of combat preparations follows a similar pattern. Pilots enter the simulation at a exponentially distributed rate with an average three pilots becoming available per hour. The exponential distribution is appropriate to represent pilots and aircraft becoming available because each successive arrival time is independent of all others. Each pilot is an individual whose schedule does not necessarily depend on the schedules of the other pilots. Similarly, each B-2 requires a different amount of time to complete its mission or maintenance before becoming available for combat preparations.

3.3.4 Sortie Duration.

Including variable duration for all of the B-2 sorties allows the model to account for for difference in targets, stopover locations and for other random variations that are inherent in air travel. Weather, wind, and aerial refueling wait times, just to name a few, can change the duration of a flight from one mission to the next.

The combat sortie durations used in the model are based on combat sorties flown during past operations and extrapolated to allow combat reach to almost any location in the world. 23 hours is selected as the minimum expected combat mission duration, 28 hours as most likely, and 34 as the maximum expected duration. These durations allow for sorties launched from WAFB to execute their combat missions and land at a stopover location. For the ferry missions (returning B-2s and pilots back to WAFB from the stopover location) 20 hours, 24 hours, and 26 hours are used for the minimum, most likely, and maximum sortie times, respectively. The ferry missions are shorter than combat missions because they are more direct flights from the stopover location to WAFB.

3.3.5 Flying Hour Restrictions.

Much like the inputs to the crew rostering problem illustrated in Figure 1, the B-2 pilots' schedules can only be feasible if certain rules and activities are satisfied. Air Force flight safety rules limit the number of hours that pilots may fly within each 7-day, 30-day, and 90-day period. The maximum allowable flying times are 56 flying hours per 7 consecutive days, 125 flying hours per 30 consecutive days, and 330 flying hours per 90 consecutive days [6:63]. Since the operational scenario runs for 90 days, the model must avoid assigning pilots to missions which would cause them to go over any of these limits during any mission.

Checks for these restrictions are implemented as a submodel, consisting of seven DECIDE blocks in a waterfall-like structure. This submodel is executed for each pilot before they are assigned to an aircrew and a mission. There are two time elements addressed in this logic; the rolling 7-day, 30-day, and 90-day windows, and the total flying times within those windows. Two of the DECIDE blocks check whether the current simulation time has reached 7 or 30 days. If these milestones have not yet been reached, the next level of DECIDE blocks check whether the pilot's cumulative flying time from the beginning of the simulation plus the maximum expected duration for the mission type to be flown next (combat or ferry) is greater than the 56 or 125 hour limits, respectively. If the combat scenario time has passed 7 or 30 days, the pilot entity passes to the next level of DECIDE blocks. These blocks check whether the pilot would violate the 7-day or 30-day flying hour limits if they were to fly a combat or ferry mission (either of which could potentially take the maximum expected duration). The final DECIDE block includes a check of whether the pilot could accomplish the next mission without exceeding the 90-day flying hour limit. If at any point, the pilot is unable to accomplish the next mission without potentially exceeding any of the flying hour restrictions, they must wait one day and then reaccomplish the flying hour clearance submodel.

3.3.6 Other Pilot Unavailability.

As with all schedules, there may be situations where a pilot is unavailable to fly a mission. An injured or sick pilot, for instance, would not be tasked with flying a mission and would be assigned *duties not to include flying* status (DNIF) until cleared to fly again. This occurrence is represented in the model by adding a random failure point just before the pilots are formed into aircrews. Once identified as DNIF, the pilot will have to wait until their condition improves before being reevaluated and released to fly. For pilots at Whiteman, the model assigns a 5% probability that any particular pilot is DNIF. At the stopover, only a 2% DNIF probability is assigned because the pilots will be resting and not be as likely to get injured or exposed to germs as they would normally when interacting with their families and the public.

This flight clearance process occurs at the end of the flying hour clearance submodel. Once the pilot has cleared the flight safety checks, there is a final DECIDE block which allows 95% of the pilots at WAFB, and 98% of the pilots at the stopover location, to exit the submodel and be assigned to an aircrew and a mission. The pilots who are not medically cleared to fly must wait a randomly assigned number of days and then reaccomplish the flying hour clearance submodel. At both locations, the model uses one day, two days, and 90 days as the minimum, most likely, and maximum number of days until being medically cleared. Shorter DNIF times represent minor cold-type illnesses. Longer DNIF times cover the spectrum of week-long flu up to a broken bone, which would ground a pilot for the remainder of the combat campaign.

3.3.7 Pilot Recovery Time.

Any B-2 sortie planned to exceed 16 hours is considered a *long-duration sortie* [5:55]. AFI 11-2B-2 Volume 1 provides guidance for crew rest durations before and after long-duration missions. "Aircrew and DNIF cover aircrew will be identified no later than 72 hours prior to launch" [5:79]. At the 509th BW this is accomplished by the crew schedulers in the flying squadrons. Pilots may be assigned to a future mission before they complete their current mission and recovery. This parallel sequence is not explicitly represented in the model because it would add extra, unrealistic, delays to the pilot schedules. "The aircrew will be relieved of non-mission related duties 48 hours prior to launch" [5:79]. Before each mission, but after pilot entities in the model accomplish the flying hour restriction test and medical clearance, they are batched into aircrews (consisting of two pilots) and assigned a mission. The simulation then moves them to a HOLD block for 48 hours. In this time, the pilots accomplish their mission-planning (learning routes, targets, communication channels, *etc.*) and take their preflight crew rest. Preflight crew rest is normally mandated as 12 consecutive hours, immediately preceding a sortie, in which the pilot has the opportunity to get at least eight hours of sleep. The 48 hours relief from normal duties includes time for additional preflight crew rest.

"Units are encouraged to use any reasonable means to shorten an extended crew duty day, such as using preflight crews, minimizing show times, *etc*" [5:79]. During normal operations, aircrews arrive at the aircraft one hour or more before their scheduled takeoff time in order to verify that the B-2 is in safe flying condition, has the proper weapon load, *etc.*, and to ready the plane for flight. The model assumes that other available pilots who are between missions and not resting will accomplish preflight so that the mission aircrew can proceed directly from crew rest to an aircraft readied for takeoff.

"Post-flight crew rest should be proportionate to the length of the flight duty period . . . For all long-duration sorties post-flight rest requirement is a minimum of 24 hours, plus one half hour for every time zone crossed in flight" [5:79]. Given the possible durations for both the combat and ferry missions, the model assumes that 12 time zones have been crossed and allots the pilots 30 hours to rest after a mission.

Before the aircrew begins their post-flight rest, they must accomplish a debriefing in which they make a record of any significant events during the mission as well as any issues with the aircraft which may warrant maintenance before the next mission. In the model, debriefs are assigned triangularly-distributed durations of 30 minutes, 45 minutes, and 60 minutes. Post-combat debrief at the stopover location is more extensive and includes recording target conditions, bomb damage assessment, hostile force contacts, *etc.* These post-combat debriefs are assigned triangularly-distributed durations of one hour, two hours, and three hours.

3.3.8 Pilot Deadheading.

Just after the pilot entities are generated in the simulation, the pilots to be deadheaded to the stopover location are separated from the standard mission flow. These pilots are moved to the stopover, rest, and are ready to fly ferry missions when the B-2s return from combat.

3.3.9 B-2 Turn Time.

The time between successive flights for an aircraft is called the *turn time* and is driven by post-flight and preflight maintenance activity requirements [22:3]. The Air Force further defines maintenance turn time as "the time required to prepare a returning mission-capable aircraft for another sortie. This calculation takes into account servicing of fuel, oil, and oxygen; the "look" phase of through flight inspection; and launch preparation" [4:17]. The research scenario simulated involves two operating locations, Whiteman AFB and a stopover location, with different maintenance activities driving the turn time at each.

An assumption affecting turn time at the stopover location is that a minimal number of B-2 maintenance personnel and support equipment are deployed. The only supported maintenance activities are launch and recovery, standard post-flight maintenance, and minor unscheduled maintenance necessary to enable a B-2 to be ferried back to WAFB. Post-flight maintenance at the stopover in the model is assigned a minimum of ten hours, maximum of eighteen hours, and an average duration of twelve hours. Since all pilots at the stopover location are in the rest-combat-rest-ferry pattern, there are none available to preflight the B-2s for the aircrews departing on ferry missions. Performing their own preflight does not overly extend the aircrew's duty day since the ferry missions are shorter than combat missions.

Once a B-2 lands at Whiteman AFB, any unspent munitions are unloaded and returned to the weapon storage and staging area. The simulation models this delay with 30 minutes minimum, 60 minutes average, and 90 minutes maximum. After any munitions are unloaded, post-flight maintenance is performed with the same modeled distribution as at the stopover location.

Another additional maintenance action available only at WAFB in this scenario is low-observable (LO) maintenance. As a LO (or *stealth*) platform, one of the primary advantages of the B-2 over other bombers is its small radar cross-section which is engineered to make the B-2 difficult for hostile forces to detect. This research scenario assumes that the LO coating on the B-2s skin requires some maintenance (even if minor) before each combat mission. Notional LO maintenance times used are 12, 14, and 18 hours in a triangular distribution.

3.3.10 Other Assumptions and Limitations.

The model involves several assumptions regarding B-2 operations at the stopover location. The first is that any B-2s with unexpended munitions are treated the same as empty B-2s. In reality, B-2s would likely have to be unloaded before maintenance or refueling. The second assumption is that every B-2 in the model is required to undergo post-flight maintenance at the stopover. A suggested further refinement of the model is to have B-2s with no live munitions onboard perform an engine running crew change (ERCC) if an aircrew is available and rested. During actual operations, this type of seamless scheduling would be feasible with integrated mission planning across the B-2 fleet. Finally, since this is a generic scenario, it is assumed that the stopover location has the capacity to hold all of the B-2s if necessary. Without this assumption there would need to be a constraint preventing combat missions from being launched if the stopover would not have ramp space available for another B-2 by the time it would arrive.

The entire B-2 fleet is assumed to be occupied with combat operations. Ready Aircrew Program (RAP) proficiency flights for combat-qualified pilots are canceled for the duration of the operation because all combat-qualified pilots are flying combat and ferry missions at a rate greater than RAP requirements, so additional proficiency sorties are unnecessary. Additionally, there are no B-2s available for student pilot training flights. It is assumed that the training of new B-2 pilots is put on hold and these officers assist with scheduling and other ground duties at WAFB.

The research model results and findings regarding the required number of B-2 pilots for the scenario and conditions discussed here are presented in Chapter 4.

IV. Findings and Analysis

4.1 Analysis Overview

For each of the four B-2 mission capable (MC) rates examined in this study, the simulation model is used to generate combat mission completion data for 94 combinations of pilot manning levels and number of pilots deadheaded. These factor-level combinations are referred to as *experiment treatments*.

Both of the pilot-related variables are incremented by multiples of 10. Initial exploratory model runs showed that higher fidelity input values produce output values which are so closely-spaced that they are well inside the uncertainty of the parameters included in this research version of the simulation model. Stepping the values by 10s greatly reduces the computing time required to generate the output for each scenario. Total pilot manning is varied from 40 to 180. The number deadheaded is allowed to range from zero up to the nearest multiple of 10 which is less than or equal to one half of the total number of pilots.

Each time that an experiment treatment is replicated (or re-run), different values are randomly selected for the activity durations and probabilities within the model, as discussed in section 3.1.2. With each replication, another value for the number of completed combat missions is added to the calculation of the average output for that treatment. Increasing the number of replications allows the reported average to approach the *true* average number of combat missions that the system represented by the model would support under the conditions of that experiment treatment. "Since the individual replications are independent and identically distributed," a confidence interval may be be constructed around the expected true average value, based on the number of replications and the average reported value [14:36]. A 95% confidence interval is a set of upper and lower values which contain the system's true average value with 95% probability. Replicating an experiment treatment numerous times allows the width of the confidence interval (which is centered around the average reported value) to be reduced, producing higher statistical confidence in the reported average.

Each experiment treatment in this study is run for 100 replications, which is shown to be sufficient to reduce the overall output variance to an acceptable level. The average number of combat missions completed for each treatment is the reported simulation output. This number is reported as an integer due to the level of uncertainty built into the initial research version of this model.

Table 3 demonstrates the impact of increasing the replication count on a single experiment treatment (the treatment illustrated happens to be the indicated optimum point for the 88% MC Rate). For the treatment examined, 60 replications is sufficient to reduce the width of the 95% confidence interval to the point that it includes only one value for the number of combat missions. Beyond 60 replications, with 95% confidence, the model reports 312 missions accomplished. Some experiment treatments with factor-level combinations significantly different from the indicated optimal point in each scenario exhibit greater variability in the number of missions.

Table 3. Model Output Variability Decrease with Increased Replications

				Combat Missions			Confidence Interval		
B-2s	**Pilots**	**Deadheaded**	**Replications**	**Average**	**Min**	**Max**	**Half-Width**	**Lower**	**Upper**
15	150	50	20	312	306	314	0.8437	311	313
15	150	50	40	312	306	314	0.5193	311	313
15	150	50	60	312	306	315	0.4443	312	312
15	150	50	80	312	306	315	0.3532	312	312
15	150	50	90	312	306	315	0.3259	312	312
15	150	50	100	312	306	315	0.3157	312	312
15	150	50	200	312	306	315	0.2390	312	312
15	150	50	300	312	306	315	0.1987	312	312
15	150	50	400	312	306	315	0.1678	312	312

Tables 4, 5, 6, and 7 in this chapter present the average number of combat missions observed across the 100 scenario replications of each of the 94 treatments. Each table represents one of the four scenarios for which the MC rate is held constant and only total B-2 pilot manning and the number of pilots deadheaded are varied. Common random numbers (as described in section 3.1.3) are used to further reduce the variance of the output values and increase confidence in the comparison across scenarios.

4.2 Identifying Optimal Manning

It is assumed that for the factor-level combinations explored in this research, combat capability is strictly increasing until it reaches the global maximum and that there are no local maximizing points. This research does not prove mathematically that the indicated optimal manning level is indeed the global optimum, however, the data tables and contour figures presented in this chapter suggest that this is the case. In order to be more concise, the indicated optimal pilot manning level is referred to as the *optimal* level for the remainder of this chapter.

Since the demand on the B-2 fleet for training flights during peacetime increases with the number of pilots, the smallest number of pilots which yields the largest number of combat missions is the optimal manning level. Additionally, for the combat scenario explored, travel costs increase and productivity at Whiteman Air Force Base (WAFB) decreases with the number of pilots deadheaded, thus that number is minimized as much as possible without negatively affecting total combat capability.

Using the data tables provided in each of the following sections, these minimizations are identified through the following simple algorithm:

1. Beginning with the top leftmost output value, assign a counter i to the current row and a column counter j to the current column.

2. Assign the value of the current cell (i, j) to a variable max.

3. Assign the current value of i to a variable *optimum*.
4. Assign the current value of j to a variable *deadhead*.
5. Increment the column counter.
6. If the value in the current cell (i, j) is strictly greater than *max*, overwrite *max* with the value in (i, j).
7. If the current cell (i, j) is nonempty, return to step 5.
8. If the current cell (i, j) is empty, reset the column counter j to its original value.
9. Increment the row counter i.
10. If the current cell (i, j) is empty, STOP. For the current mission capable rate, *optimum* equals the indicated optimal pilot manning level, *max* equals the maximum number of combat missions, and *deadhead* equals the best examined number of pilots to deadhead.
11. If the current cell (i, j) is nonempty, return to step 6.

The following sections present the data and findings generated by the model used in this research.

4.3 Research Model Findings at 53% MC Rate

Recall that Table 2 in section 3.3.2 lists the average number of B-2 aircraft available for flying at each of the four mission capable rates examined in this research. Those selected MC rates, and the corresponding number of available B-2s, are each used in the research model in order to generate the number of combat missions completed in a 90-day continuous combat scenario. This 53% MC rate scenario is chosen as the baseline to which the subsequent scenarios are compared.

The results with the B-2 MC rate at 53% are presented in Table 4. With only 9 B-2s available, 188 combat missions in 90 days is the maximum number possible regardless of the number of pilots. Using the optimal pilot manning level and deadheading number identification algorithm, 100 pilots is selected as the optimal total manning level. There is a plateau effect noticeable both in Table 4 as well as graphically in Figure 7. The model has identified the point of diminishing returns, above which adding more pilots does not increase the number of completed combat missions. Below this manning level, a shortage of pilots constrains the possible number of missions; above it, the mission capable rate or some activity in the aircraft schedule is the constraining factor.

Table 4. Combat Capability at 53% Mission Capable Rate

Total B-2 Pilots	Number Deadheaded 0	10	20	30	40	50	60	70	80	90
40	94	104	83							
50	95	128	121							
60	95	143	150	125						
70	95	145	173	161						
80	95	145	181	183	162					
90	95	145	181	187	184					
100	95	145	181	**188**	187	183				
110	95	145	181	188	188	187				
120	95	145	181	188	188	187	186			
130	95	145	181	188	188	187	187			
140	95	145	181	188	188	187	187	186		
150	95	145	181	188	188	187	187	186		
160	95	145	181	188	188	187	187	186	185	
170	95	145	181	188	188	187	187	186	185	
180	95	145	181	188	188	187	187	186	185	185

It must be noted that on the contour plots such as Figure 7, only the intersection points of the two factors are generated from the model output data. The contour lines shown between the intersections are an artifact of the graphing software, and are not likely to be accurate.

Under the assumptions and uncertainties inherent in this model, if the B-2 MC rate remains near its 2010 value (which is just above the rate used in this scenario) the 509th Bomb Wing is currently manned at the optimal level. If called on to perform a continuous combat rotation, deadheading 30 pilots would yield the highest combat mission throughput possible. However, the limitations and additional research sug-

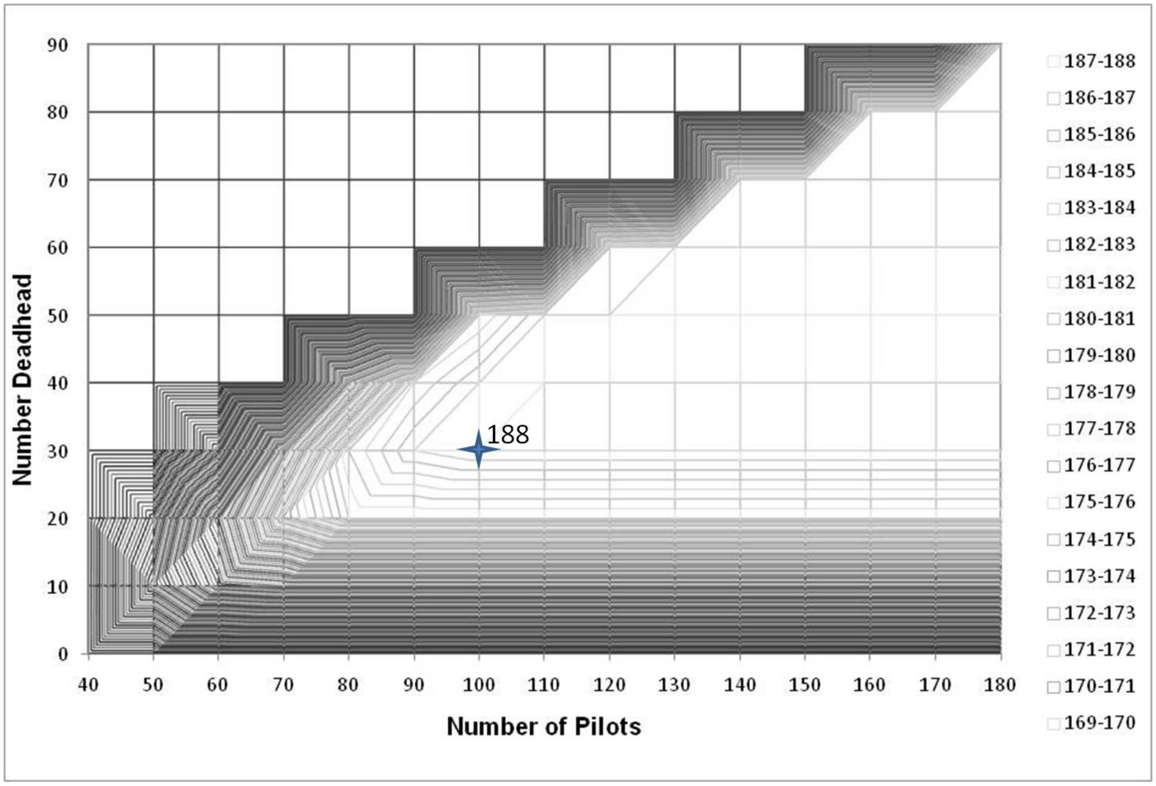

Figure 7. Contour Plot of Combat Capability at 53% Mission Capable Rate

gestions presented in section 5.3 are vital to understanding the degree of applicability of this assessment.

4.4 Research Model Findings at 65% MC Rate

A B-2 fleet mission capable rate of 65% translates to 11 aircraft on average available for flying operations. The results from running the model under these conditions are listed in Table 5 and illustrated in Figure 8. The smallest maximum number of combat missions achievable is 104; 10 higher than the smallest value for the previous scenario solely because of the addition of two aircraft. The optimal combination of pilot manning and deadheading here is found to be 110 pilots with 40 of them deadheaded. In this case, the greatest number of combat missions executed in 90 days is 229, more than double the lowest total under this scenario. Adding 10 pilots to the baseline level of 100, in addition to increasing average aircraft availability to 11 B-2s, total combat capability is 41 sorties greater than the maximum with 53% MC.

Table 5. Combat Capability at 65% Mission Capable Rate

Total B-2 Pilots	Number Deadheaded 0	10	20	30	40	50	60	70	80	90
40	104	105	84							
50	116	131	121							
60	117	153	153	126						
70	117	166	179	164						
80	117	168	199	194	166					
90	117	168	210	218	202					
100	117	168	211	226	223	203				
110	117	168	211	227	**229**	224				
120	117	168	211	227	229	228	223			
130	117	168	211	227	229	229	228			
140	117	168	211	227	229	229	228	227		
150	117	168	211	227	229	229	228	227		
160	117	168	211	227	229	229	228	227	227	
170	117	168	211	227	229	229	228	227	227	
180	117	168	211	227	229	229	228	227	227	226

Scanning down the columns of any of the tables of results in this chapter confirms one hypothesis of this research. Each column, taken individually, contains the number of combat missions completed as the pilot manning level is varied, but fleet MC rate and number of pilots deadheaded is held constant. As an example, the first column of Table 5 represents a 65% MC rate and not deadheading any pilots to the stopover. Under these conditions, the number of combat missions stops increasing at 60 pilots. This plateau effect is seen in every column of the four peformance measure tables in this chapter.

4.5 Research Model Findings at 76% MC Rate

If the conditions are in place for the B-2 fleet to be available at a 76% mission capable rate, on an average day 13 aircraft are able to be flown. The results from running the model under these conditions are listed in Table 6 and illustrated in Figure

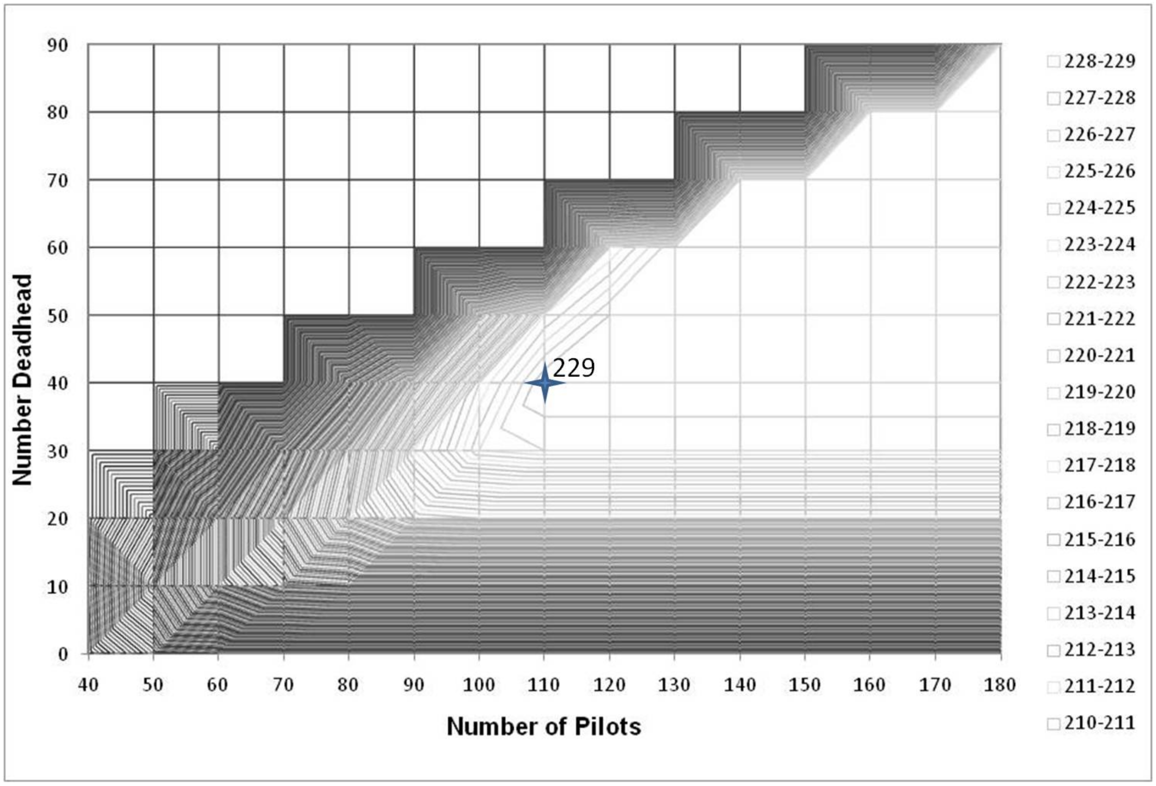

Figure 8. Contour Plot of Combat Capability at 65% Mission Capable Rate

9. The optimal number of pilots is 140, a significant increase over the baseline. 40 of these pilots are selected to be deadheaded to the stopover point and form the initial cadre of pilots which ferry the B-2s back to WAFB after the combat missions. 271 combat missions are launched during the 90-day operation. This improvement of 83 missions over the baseline requires 40 additional pilots.

It is interesting to note that the smallest maximum number of combat missions achievable increases by only 13 from the baseline, to 107. Using the notional parameter values, the model identifies that in the case with 40 pilots and 13 aircraft, pilot manning has again become the limiting factor.

Also of note in Table 6, the cell just above the optimal value of 271 missions contains the same value (270) as the cells below the optimum. This is an example of the effect of the randomness built into the model to represent durations of actual

Table 6. Combat Capability at 76% Mission Capable Rate

Total B-2 Pilots	Number Deadheaded 0	10	20	30	40	50	60	70	80	90
40	107	105	84							
50	128	132	122							
60	138	158	153	126						
70	139	178	181	165						
80	138	189	206	198	167					
90	138	189	224	225	205					
100	138	189	234	248	238	208				
110	138	189	236	262	261	242				
120	138	189	236	264	269	263	243			
130	138	189	236	264	270	269	264			
140	138	189	236	264	**271**	270	268	263		
150	138	189	236	264	270	270	269	268		
160	138	189	236	264	270	270	269	269	267	
170	138	189	236	264	270	270	269	269	268	
180	138	189	236	264	270	270	269	269	268	267

maintenance and operations activities, not known with certainty. Two identical activities performed under nearly identical conditions may have different durations for any number of reasons. One example from aircraft maintenance is that a "dropped tool" event can occur when a tool, fastener, or some other small part goes missing during a maintenance activity. All maintenance stops until the item is found because any foreign object left in the inner workings of an engine could have catastrophic effects. By contrast, the majority of the 100 model runs under these conditions happened to benefit from shorter randomly-drawn activity times and, on average, one additional combat mission was completed over the apparent upper limit.

4.6 Research Model Findings at 88% MC Rate

The final scenario examined in this research is the case in which the B-2 fleet sustains a mission capable rate of 88%. This MC rate leads to an average of 15 of the total 20 aircraft available at any time. Table 7 and Figure 10 present the results for this scenario. 312 combat missions is the average maximum number generated by

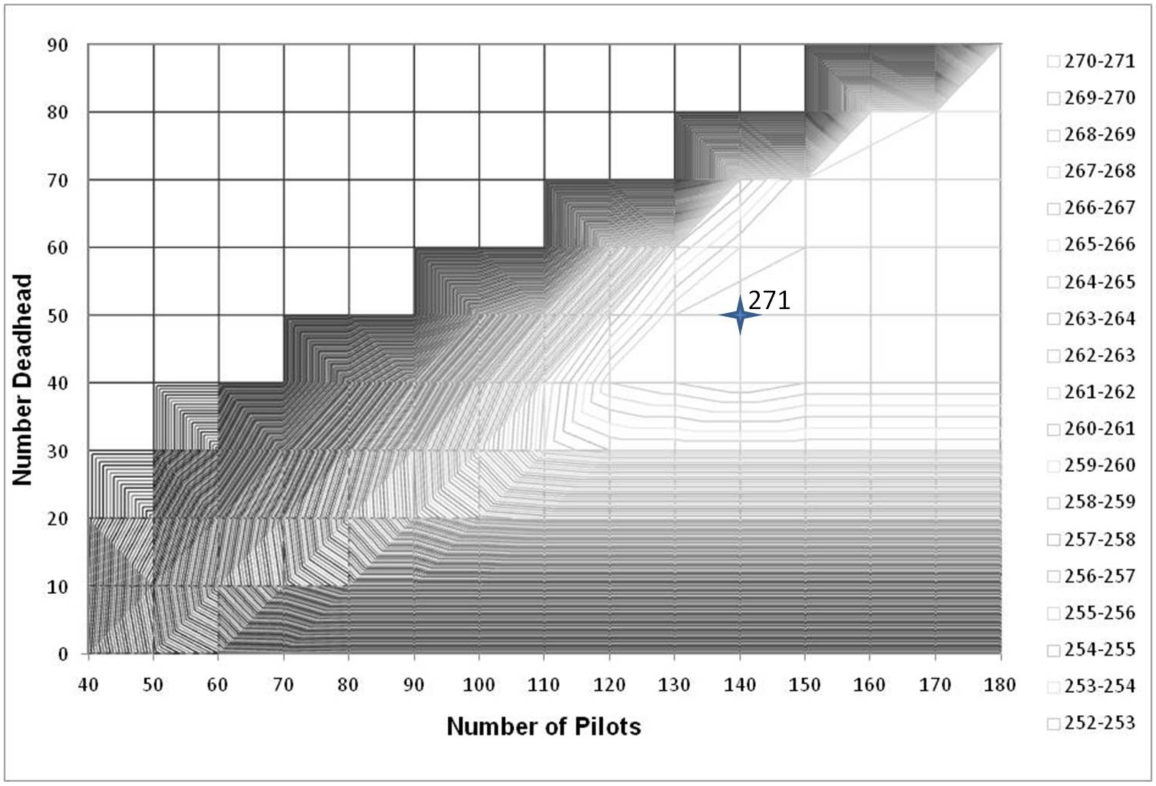

Figure 9. Contour Plot of Combat Capability at 76% Mission Capable Rate

the model at this MC rate, with the optimal pilot and deadheading combination. 150 pilots are required, with 50 of them deadheaded, in order to achieve the 312 missions.

This scenario requires an average increase in availability of 6 aircraft over the baseline rate of 53%, and would also require increasing the total number of B-2 pilots well over the baseline level of 100. Referencing Table 10 in Appendix B, it is evident that in 2010 no US Air Force manned aircraft fleet sustained a mission capable rate above 85%. Consequently, this final research scenario is very likely above the feasible upper limit of performance achievable for the B-2. However, further refinements in the model, as suggested in section 5.3, are required before using it for any decision-quality analysis along these lines.

Table 7. Combat Capability at 88% Mission Capable Rate

Total B-2 Pilots	Number Deadheaded 0	10	20	30	40	50	60	70	80	90
40	108	105	84							
50	133	133	122							
60	153	159	154	126						
70	159	183	182	165						
80	160	201	209	199	169					
90	160	209	232	228	207					
100	160	211	249	254	241	209				
110	160	211	258	276	270	248				
120	160	211	259	291	294	279	250			
130	160	211	259	296	306	302	282			
140	160	211	259	297	309	309	303	282		
150	160	211	259	297	309	**312**	309	303		
160	160	211	259	297	309	312	311	309	303	
170	160	211	259	297	309	312	311	310	308	
180	160	211	259	297	309	312	311	310	309	307

4.7 Deadheading Findings

For a given total number of pilots assigned, deadheading a portion of them to the stopover location at the start of combat operations is shown to increase the number of combat missions that the 509th BW is able to deliver. Table 8 is similar to the tables of combat mission count output, but it simply shows how many pilots remain at WAFB as the main contingent. When these pilots are not in the pre- or post-mission rest cycles, they are available to perform their normal management and training duties which allow the B-2's operations to continue to run smoothly. They are also closer to their families and sleeping in their own beds, factors which reduce the stress of combat and allow for better focus on the mission.

The cells corresponding to the optimal pilot and deadheading levels for all four MC scenarios are highlighted in Table 8. Each of these identified combinations results in retaining between 64% and 72% of the pilot force at Whiteman AFB. This suggests that, for an optimally-manned pilot force, deadheading one-third of the available

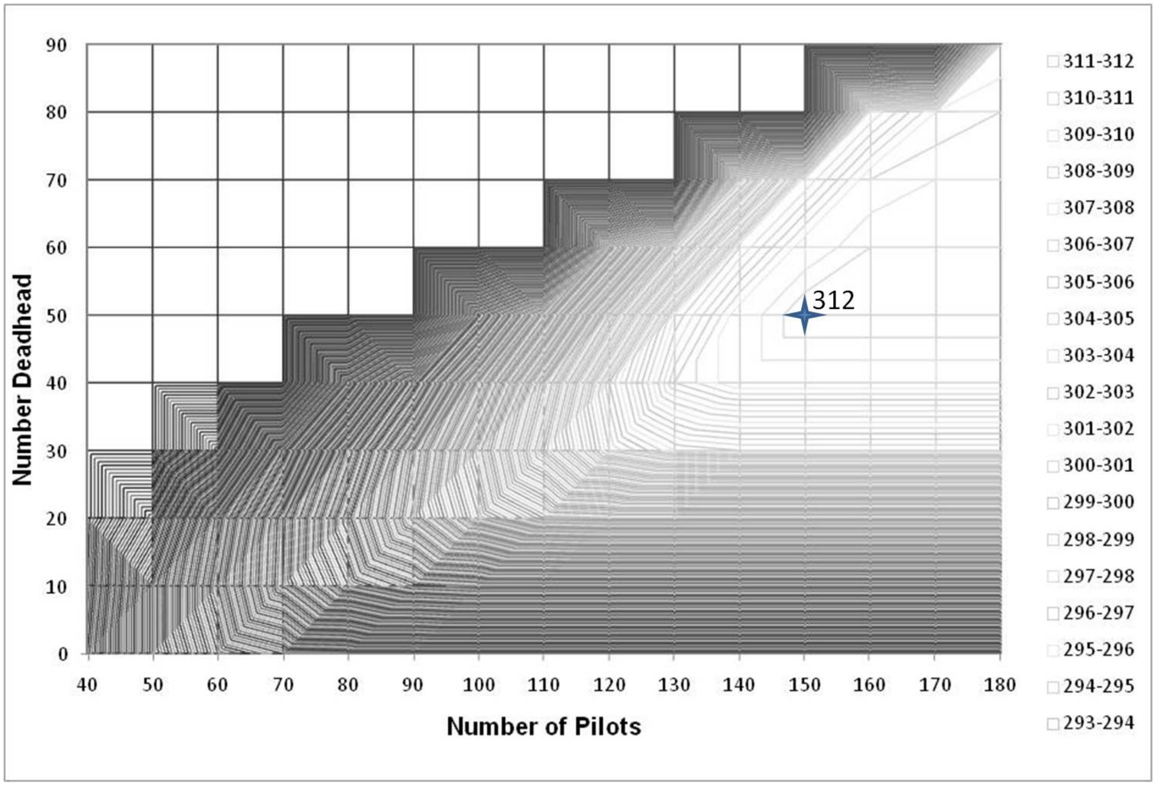

Figure 10. Contour Plot of Combat Capability at 88% Mission Capable Rate

pilots to the stopover location may be used as a guideline for general planning in the absence of further detailed analysis.

4.8 Summary

As hypothesized, combat mission capability under each examined mission capable rate plateaus at the optimal pilot manning level. The identified optimal manning level for a particular fleet MC rate allows the 509th Bomb Wing to execute the most sorties possible in a combat scenario while avoiding the accumulation of excess wear on the airframes due to peacetime training. Also, for manning levels at or above the optimum, combat mission capability is seen to decrease if the number of pilots deadheaded is too great. An additional finding is that if only a fixed number of pilots (fewer than optimal) can be assigned to the combat rotation, the model may be used

Table 8. Pilots Available at Whiteman AFB Decrease with Increased Deadheading

Total B-2 Pilots	Number Deadheaded									
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
40	40	30	20							
50	50	40	30							
60	60	50	40	30						
70	70	60	50	40						
80	80	70	60	50	40					
90	90	80	70	60	50					
100	100	90	80	**70**	60	50				
110	110	100	90	80	**70**	60				
120	120	110	100	90	80	70	60			
130	130	120	110	100	90	80	70			
140	140	130	120	110	**100**	90	80	70		
150	150	140	130	120	110	**100**	90	80		
160	160	150	140	130	120	110	100	90	80	
170	170	160	150	140	130	120	110	100	90	
180	180	170	160	150	140	130	120	110	100	90

to determine the proportion of those pilots to deadhead in order to maximize combat mission throughput.

Chapter 5 presents a brief discussion on the overall conclusions and recommendations generated by this research effort.

V. Summary and Conclusions

5.1 Summary

In support of US Air Force and Department of Defense efforts to conserve resources without sacrificing capability, this research examines B-2 pilot manning for the 509th Bomb Wing. Development of a discrete-event simulation model allows the indicated optimal pilot manning level to be identified for an expected fleet readiness level. Optimal pilot manning ensures that the maximum possible number of combat missions may be delivered when the B-2 is employed in a conflict. Further, limiting pilot manning to the identified optimal level decreases the accumulation of excess wear on the B-2 airframes; extending the viable life of the fleet and safeguarding the deterrent and combat capabilities that the B-2 provides to the United.

The 90-day combat scenario modeled satisfies flight safety restrictions on pilot scheduling and uses stochastically-generated durations for the operations and maintenance activities required for sustained combat operations.

5.2 Conclusions

The scenario and notional model parameters used in this research do not support a recommendation to decrease B-2 pilot manning. Section 5.3 details the major limitations of this research and provides recommendations for future work to generate more precise results, potentially leading to different recommendations for the 509th Bomb Wing.

At each of the four levels of B-2 fleet mission capable (MC) rate studied, output from the model developed in the course of this research includes a point of diminishing returns. Pilot manning above this identified level does not increase the number of combat missions which may be launched during the 90-day scenario, and increases peacetime wear on the B-2 aircraft. Below this manning level, the number of trained and available pilots constrains the possible number of missions. With manning above the indicated level, some activity in the aircraft schedule or the number of aircraft available under the current mission capable rate is the constraining factor.

This research also determines a general planning factor which the 509th BW may use when conducting combat operations from Whiteman AFB (WAFB) and post-combat ferry missions from a stopover location. For an optimally-manned B-2 pilot force, deadheading approximately one-third of the available pilots to the stopover location results in the highest number of completed combat missions, and allows pilots not in the combat and ferry mission cycle to focus on their duties at WAFB.

5.3 Limitations and Areas for Additional Research

The notional, unclassified estimates used to generate operations and maintenance activity durations in the research model are known to be inaccurate. Further study of the pilot manning level at the 509th Bomb Wing is planned and should incorporate actual historical activity durations as the parameters for the triangular distributions in the simulation model. Analysis of historical data may suggest that a statistical distribution other than triangular (*i.e.*, beta, gamma, or Weibull) is a better fit for activity durations. The two other stochastic values used in the model are the pass/fail probability for a pilot's preflight medical clearance and the probability that a B-2 returns from combat without all munitions having been expended. These probabilities should also be updated with historical data from the 509th BW.

Higher-fidelity input data allows the model to generate more precise capability assessments. After running the model with a broad range of independent variable values, as was done in this research, it is suggested that follow-on work focus on the neighborhood around the indicated optimum point in each scenario. Decreasing the increments used for the experiment treatments and tailoring their scope for each specific scenario will allow more data points to be investigated within the area of interest. Computing time will be better spent running more replications in a narrower region in order to decrease output variability. These techniques will allow follow-on work to more accurately identify the level at which pilot manning is optimal for a specified expected mission capable rate.

There may be two or more buffers built into the formal manning level. These are not addressed in this research, but could be added on top of the findings from a higher-fidelity version of the model. One type of positive buffer would be the addition of extra B-2 pilots required to keep the current manning level at WAFB at the proper level while making up for pilots who are in assignments away from WAFB. Another type of buffer, that could lower the required manning level, would be to not assign B-2 pilots to the various staff functions across the wing. The model used in this research assumes that pilots are allowed to focus on their flying proficiency and combat qualifications. In this case, the staff positions at the wing and squadron levels would be filled by officers with the proper experience but not currently on flying status (possibly not even B-2 pilots). These officers would not be required to maintain currency in the B-2, thereby saving wear on the fleet. However, employing staff officers in addition to B-2 combat pilots could potentially generate higher manpower costs than the savings from reduced B-2 wear justifies.

5.4 Recommendations

The model development methodology employed in this research – incorporating realistic scheduling constraints and all applicable flight, maintenance, and pilot activities – is applicable to any small aircraft fleet which has an objective of maximizing the number of flights completed. The greatest gain may be realized by flying organizations which expend the majority of their flying hours on pilot training and proficiency.

Beyond the identification of an optimum number of pilots, aircraft fleet managers face additional manning decisions based on risk prioritization and may be able to further increase fleet longevity. Pilot manning at the optimum level may be employed in order to provide the maximum capability when required, until the aircraft fleet can no longer support the required activity level. Optionally, if a decreased maximum capability is acceptable, leadership may choose to staff pilots at a suboptimum level. Suboptimal pilot manning would result in even greater reductions to fleet wear and would preserve the airframes even more, allowing the fleet the ability to operate at the chosen capability level and support pilot currency requirements further into the future.

Appendix A. Operational Scenario ARENA Model

Table 9. Simulation Model Notional Distribution Parameters

Block Name	Action	Distribution	Units	Min	Mode	Max	CRN Stream
Assign CombatDuration	Assign	Triangular	Hours	23	28	34	20
Assign FerryDuration	Assign	Triangular	Hours	20	24	26	50
Deadhead Flight	Delay	Triangular	Hours	30	36	40	160
Debrief_S	Delay	Triangular	Hours	1	2	3	30
Debrief_W	Delay	Triangular	Hours	0.5	1	1.5	60
Fuel and Preflight_S	Delay	Triangular	Hours	1.5	2	2.5	150
Fuel and Preflight_W	Delay	Triangular	Hours	1.5	2	2.5	10
LO MX	Delay	Triangular	Hours	12	14	18	90
Mission Plan and Crew Rest_S	Delay	Constant	Hours		48		
Mission Plan and Crew Rest_W	Delay	Constant	Hours		48		
PostFlight MX_S	Delay	Triangular	Hours	10	12	18	40
PostFlight MX_W	Delay	Triangular	Hours	10	12	18	80
Recover_S	Delay	Constant	Hours		30		
Recover_W	Delay	Constant	Hours		30		
ShutDown_S	Delay	Constant	Hours		1		
ShutDown_W	Delay	Constant	Hours		1		
Unload Weapons	Delay	Triangular	Hours	0.5	1	1.5	70
Weapon Load	Delay	Triangular	Hours	1	2	4	100

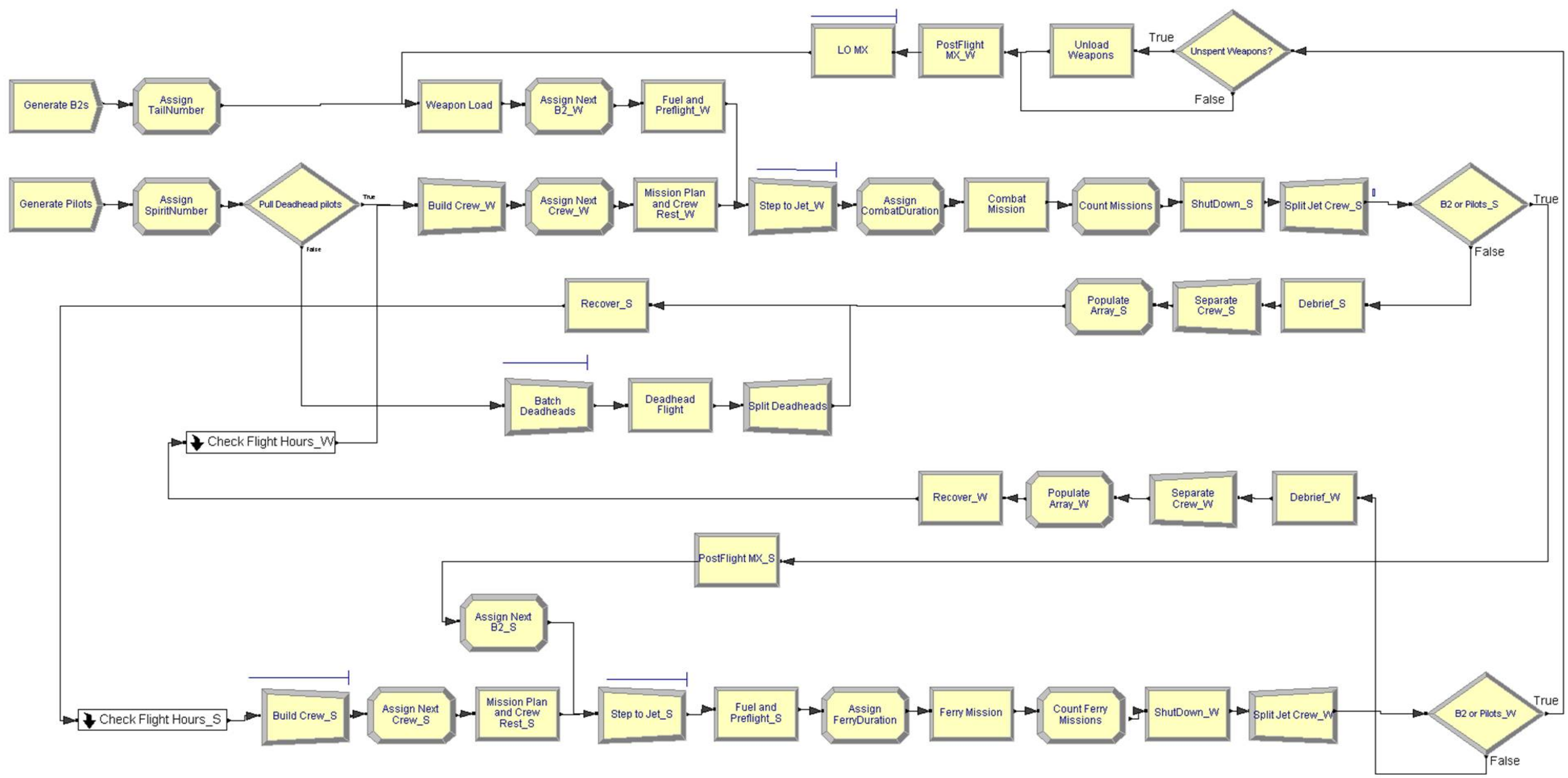

Figure 11. Simulation Model Structure

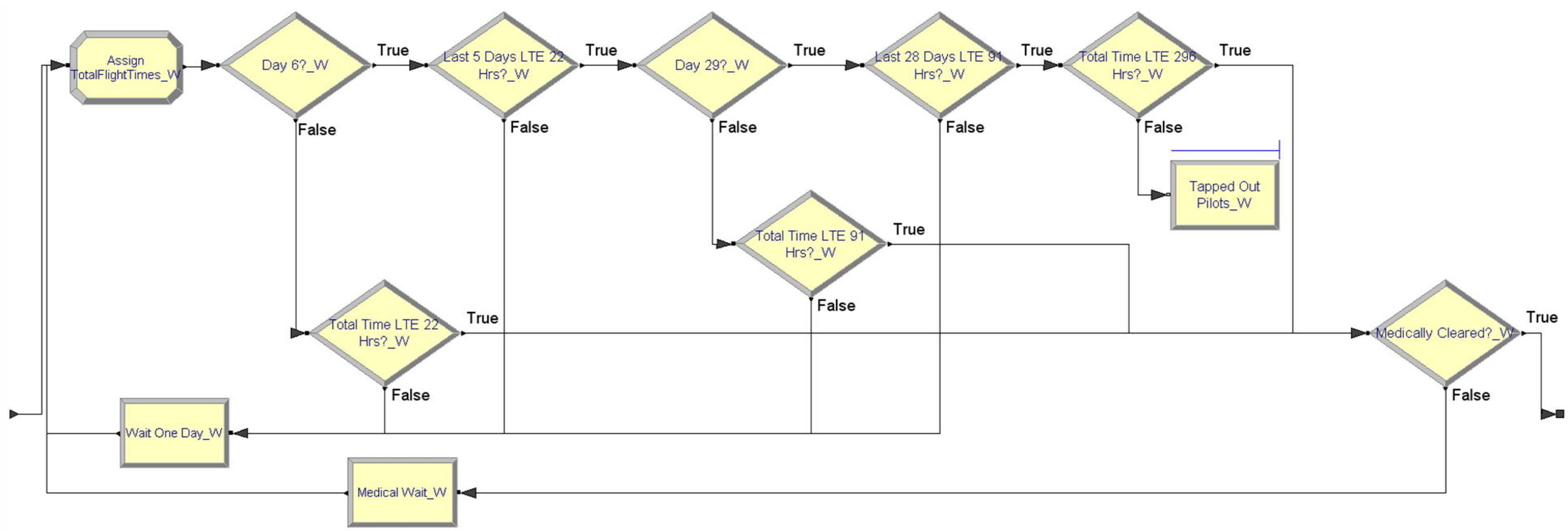

Figure 12. WAFB Flight Hour Check & Medical Clearance Submodel Structure

Appendix B. FY 2010 Air Force Mission Capable Rates

Table 10 lists the published fiscal year 2010 mission capable (MC) rates for all Air Force aircraft systems (adapted from [19]). Average mission capable (MC) hours per aircraft per week is calculated by Equation (5). Average not mission capable (NMC) hours per aircraft per week is calculated by Equation (6).

Table 10. FY 2010 Air Force Mission Capable Rates and Weekly Aircraft Availability

Aircraft	MC Rate	MC hours per week	NMC hours per week
Q-4	41.64 %	70	98
B-1B	43.82 %	74	94
C-5A	52.66 %	88	80
CV-22	54.30 %	91	77
B-2	54.86 %	92	76
C-5B	59.59 %	100	68
F-22	60.94 %	102	66
EC-130J	65.17 %	109	59
HC-13	69.90 %	117	51
A-10	70.46 %	118	50
EC-130H	70.62 %	119	49
F-15C	70.96 %	119	49
E-3	71.60 %	120	48
F-15E	72.46 %	122	46
C-130H	73.85 %	124	44
B-52H	74.61 %	125	43
HH-60	74.65 %	125	43
KC-10A	74.78 %	126	42
F-16	75.39 %	127	41
T-38C	76.15 %	128	40
C-130E	76.67 %	129	39
T-1A	79.73 %	134	34
T-6A	80.34 %	135	33
T-38A	80.41 %	135	33
KC-135T	80.41 %	135	33
UH-1	80.87 %	136	32
KC-135R	81.06 %	136	32
E-8	81.08 %	136	32
U-2	81.22 %	136	32
C-130J	82.27 %	138	30
C-17A	84.43 %	142	26
MQ-9	91.95 %	154	14
MQ-1	92.98 %	156	12

Appendix C. Blue Dart

B-2 Pilot Manning for Increased Aircraft Longevity and Mission Capable Rates

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Three US Air Force B-2 Spirit bombers struck 45 targets inside Libya on the opening night of Operation Odyssey Dawn. The B-2 provides the unique capability to strike deep inside hostile airspace and cripple air defenses, allowing other coalition aircraft to execute their missions from a superior position. But could it be possible that the requirement to have a sufficient number of pilots trained and ready for major combat operations is actually wearing out the B-2 fleet? The Air Force Institute of Technology (AFIT), working with the 509th and 131st Bomb Wings at Whiteman Air Force Base (AFB) and Air Force Global Strike Command (AFGSC) at Barksdale AFB, is researching a potential relationship between the number of B-2 pilots and the expected lifespan of the B-2 fleet.

The crash and total loss of one B-2 at Anderson AFB in 2008 leaves the fleet with only 20 aircraft; 19 at Whiteman AFB for operations and training, and one assigned to Air Force Flight Test Center at Edwards AFB. Of the 19 at Whiteman, however, only about half are available at any given time to be used for peacetime flying. Why is this so? There are four main reasons: As an operational bomber, several B-2s are always kept available for real-world contingency use. At any given time, approximately three B-2s are in programmed depot maintenance (PDM), a one-year complete overhaul process. One or two B-2s are often parked for several months at a time for the installation of upgraded components (communications equipment, radars, *etc.*). Finally, there are occasionally a few B-2s awaiting replacement parts.

The remaining B-2s have to accommodate the entirety of the 509th and 131st Bomb Wings' daily peacetime flying activities; the majority of which involve pilots being trained or maintaining currency. Other B-2 flying requirements are for testing of upgraded software and components under operational conditions, flight safety verification after PDM or other major maintenance, and advanced tactics training for pilots in Weapons School (think Top Gun). As pilots retire, new pilots are trained to replace them; each requiring an average of fifty hours of training flights.

Much like airline pilots, fully-trained B-2 pilots are required to log at least a minimum number of flight hours per month in order to "stay current" by Federal Aviation Administration safety standards. However, unlike airline pilots who can stay current during their normal work schedule, a B-2 pilot's job is to fly combat missions — which doesn't happen often. During peacetime they are required to stay current by flying what amount to extra training missions, simulating their combat duties. This separation between wartime mission execution and peacetime training separates military combat pilots from airline pilots and even from most military transport pilots. Combat aircraft can actually accumulate more wear due to training than due to their combat missions.

One aspect of the flying requirements placed on the B-2 fleet that the Bomb Wings could potentially control is the total number of pilots. The current Air Force approach to this issue is to separate pilots by their tasking level. Combat pilots focus on training and preparation for combat. They are assigned day-to-day jobs, but nothing that will take their focus away from proficiency training for too long. Staff pilots, in leadership positions, focus on the management of the flying organizations and are only required to fly half as many hours per month as the combat pilots. If the 509th and 131st could perform their combat taskings with fewer pilots overall, and find the proper balance between staff and combat pilots, they could lessen the stress that training and monthly proficiency flights put on each of the B-2 aircraft.

Using computer simulation, the first phase of this AFIT research involved building a model which represents all of the maintenance and operations activities which would make up the schedule for the B-2 aircraft and pilots if they were called upon to fight a drawn-out war. The simulation is used to identify the overall pilot manning level which allows the maximum possible number of combat missions to be launched under a given set of maintenance and aircraft availability constraints. Through the refinement and use of this model, the 509th and 131st Bomb Wings and AFGSC will be able to gain insight into the effect of pilot manning on combat capability and the training load on the B-2 fleet.

Captain Jason Hamilton is a recent graduate of the Air Force Institute of Technology.

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Vita

Captain Jason S. Hamilton was homeschooled in Waco, Texas and graduated in 1997. He accomplished his undergraduate studies at McLennan County Community College and Baylor University. In May 2003, he graduated from Baylor University with a Bachelor of Science degree in Applied Mathematics with a minor in Engineering. Jason was commissioned into the US Air Force through AFROTC Detachment 810.

Captain Hamilton's first assignment was to the 72d Test and Evaluation Squadron at Whiteman AFB, Missouri. Jason performed test director and analyst duties for several major test projects, including the Nuclear Weapon System Evaluation Program and the B-2's integration of the 500-pound MK-82 JDAM.

In August 2006, Jason was assigned to Detachment 4 of the Air Force Operational Test and Evaluation Center (AFOTEC) at Peterson AFB, Colorado. He provided test analysis to space acquisition programs including Space Based Space Surveillance and Wideband Global SATCOM.

In 2008, while assigned to AFOTEC, Jason deployed to the US Air Forces Central (USAFCENT) Combined Air & Space Operations Center (CAOC) for three months and served as the Afghanistan Operations Analyst on the CAOC's Operational Assessment Team.

Also while in Colorado, Captain Hamilton was selected to be in the initial class of the Space Education Consortium; a joint program between Air Force Space Command and the University of Colorado at Colorado Springs (UCCS). Jason completed the program in April 2009; earning a Master's Certificate in Space Systems Management from UCCS.

In August 2009, Jason entered the Air Force Institute of Technology's Graduate School of Engineering and Management at Wright-Patterson AFB, Ohio. At AFIT, he focused his studies on Deterministic Operations Research and Operations Modeling. Upon graduation, he will be assigned to the Air Force Personnel Center's Analysis Branch at Randolph AFB, Texas.

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14. ABSTRACT In support of US Air Force efforts to conserve resources without sacrificing capability, this research examines the question of whether the 509th Bomb Wing could continue to provide maximum combat capability with fewer assigned pilots. During peacetime, pilot proficiency training comprises the majority of annual flying hours for the small B-2 bomber fleet. Optimal pilot manning will decrease the accumulation of excess wear on the airframes; helping to extend the viable life of the B-2 fleet and preserve the deterrent and combat capabilities that it provides to the United States.

The operations and maintenance activity flows for B-2 aircraft and pilots in a notional sustained combat scenario are constructed in an Arena discrete-event simulation model. The model provides the capability to determine optimum manning levels for combat-qualified B-2 pilots across a range of fleet mission capable rates. Determination of actual optimum manning levels is sensitive to duration and probability parameters which are unavailable for use in this work. Notional parameter estimates are used to assess combat mission capability and pilot manning.

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